Limited emission dredging

Design of a decision-making tool aimed at the technically, economically and socially feasible reduction of dredging fleet emission

Master Thesis report (SPM 5910)

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Summary

Dredging is a fast growing highly competitive industry in which performances are purely assessed on economic feasibility. Currently, maximal production is the only performance indicator used throughout a contractor agency. With increasing public attention to environmental goals, climate change and emission the dredging industry is developing an interest in new performance indicators that take into account their emission performances.

Sustainable development requires environmental, economical and social feasibility. Technologically, an abatement method needs to significantly reduce the amount of emission. At the same time such a method needs to be economically feasible and socially acceptable so the stakeholders involved will support the method. This research was aimed at the investigation of possibilities of emission abatement and the design of a decision-making tool that fulfils the above mentioned requirements of sustainable development.

To do so the following research questions have been investigated:

How can the emission of gases (CO_2, SO_x, NO_x and PM) be reduced by operational improvement in a technically, economically and socially feasible way?

To answer this question a number of sub-questions is formulated:

1) What amount of gaseous emission does the fleet produce?
2) What are the consequences of emission of the fleet?
3) What factors can be identified to influence the amount of emission?
4) How can operational improvement influence the factors to change the amount of emission?
5) What types of organisational changes are required within a dredging company to implement operational measures, aimed at reducing the amount of emission?

Problem analysis

The problem analysis describes the 'dredging operation system' from a technological, process and institutional perspective:

The technical analysis provides an overview of emission types and their effects. Several emission abatement methods have been analysed to generate an overview of possibilities and to enable selection of the most appropriate method for this research. Reducing fuel consumption by 'Vessel Speed Reduction' has been selected for further investigation. This method has a positive effect on all gaseous emission types, since fuel consumption is directly – or almost directly – related to the emission types under consideration. Operational improvement is relatively easy to implement without a necessity for new built or retro fit. The method is suitable for application on all vessels at all times (including new built) and will still be effective if combined with other (more technical) abatement methods. Finally, the reduction in fuel consumption cuts fuel costs, which makes the method interesting from an economic perspective.

The process and institutional perspective show the relationship between the dredging contractor and the rest of the stakeholders – categorized in the groups: subcontractor, client, authorities and external stakeholders – and analyse what process aspects need to be taken into account for operational improvement. The process perspective shows that there is a strong principal-agent relation between the head office and vessel staff of a dredging organisation. This relation creates the agency problems: I) asymmetry in information, II) hidden characteristics and III) hidden intentions, which need to be resolved for successful process change.

The institutional perspective provides an overview of the different institutions and how they affect the system. It shows that most institutions have a technical focus and that emission units that take into account the efficiency of the complete system ('Performance Standard Rate') are not likely to be acknowledged as valid reduction methods. Since this research does aim at improving the 'Performance Standard Rate' of emission, sincere attention should be paid to the communication with external stakeholders and authorities to help them recognise the potential of this method of abatement.

Field study
The dredging contractor Boskalis provided the possibility to do a field study for this research. On the trailing suction hopper dredger 'Queen of the Netherlands' the operational actions, the fuel consumption and the vessel speed have been monitored during a trial period of ten days. The specific objective was to localize the feasible region for operational change.

Reference measurements were designed to provide information about the exact fuel consumption of the vessel per phase of the dredging cycle. Experiments were held to analyse what the effect of changes in operational behaviour are on the fuel consumption. A series of experiments has been carried out, in which the variation steps were rather large to analyse a wide range of possibilities, rather than to determine vessel speed as precisely as possible.

The results describe the translation of data on fuel consumption and vessel speed, to performance indicators that are interesting to a dredging company. A mono-objective function is utilised that translates all output into financial costs, since economic feasibility is the dredging contractor's key-objective.

Decision-making tool
A decision-making tool (spread sheet model) is designed, that enables the user (contractor) to calculate the effect of changes in environment variables on the performance indicators. Via the scenario-axes 'fuel price', 'emission price' and 'market price of dredged material' the most feasible capacity option can be selected for each defined scenario.

The model is also capable to calculate the effect of 'Vessel Speed Reduction' on the complete dredging cycle within a cycle estimation sheet. This sheet shows how by reducing vessel speed the contractor can substantially lower the 'Performance Standard Rate' of emission and fuel costs of a specific project by sacrificing a small amount of operation time to longer sailing.

A change in the acceleration method saves a considerable amount of fuel during the acceleration period, which is likely to be economically feasible to the contractor. However, a contractor should carefully consider whether the effort of standardizing the acceleration phase is appropriate for the result. On the total fuel consumption of the vessel the potential reduction would be marginal. Moreover, the optimization of the acceleration phase will be difficult to implement because each Officer knows his own method and the acceleration phase is highly valued within the work appreciation of vessel staff.

Process design
The transition from the performance indicator maximal production to minimal emission will not be without challenge within the conservative dredging sector. When aiming to solve the existing agency problems within the company this research stresses the risk of traditional approaches like ´monitoring´ and ´incentives´. The process design describes a system of creating commitment by communication. The vessel staff needs to be motivated for the new objectives by receiving information over the effect of their actions on performance indicators; and by creating a sport in minimizing emission. Moreover, to provide a real-time visualization on board for the performance indicators 'fuel consumption', 'emission' and 'costs', will enable Officers to directly see the effect of their actions on the company objectives; without constraining their high level of autonomy

Evaluation
As described the purpose of this research was to identify a feasible region rather than provide exact values. If the feasible region is identified the values of relations require further validation, on similar and on different vessel types. For the development of an on board real-time decision-making support system, cooperation with a research institute can be useful. If the financial objective becomes less dominant the scenario-analysis should be developed further into a multi-objective program, which enables the user to see the separate values of sub-objectives such as emission production.

Preface

This is the final report of my Thesis for the Master of Science program Systems Engineering, Policy Analysis and Management, carried out for Royal Boskalis Westminster nv. The research was carried out between July 2007 and March 2008 in the Netherlands and at dredging projects in Dubai and Qatar.

I would like to thank my supervisors from the TU Delft Zofia Lukszo and Scott Cunningham; from Royal Boskalis Westminster NV Rick Maliepaard and Harry Hesseling and my professor Margot Weijnen, that all found the time and interest to help me fulfil this job.

I would especially like to thank the staff of the vessel 'Queen of the Netherlands', Ton and Adri for their general cooperation and support; Wim for his great efforts to enable all data gathering; Frank, Arjan, Maarten, Marco, Marco and Harm; for helping me understand the engines Peter and Wout for showing me around the vessel and Perry, Hans, Saat, Arjan and Marc without whom I would never have been able to perform my experiments. But most of all everyone I could not mention for all the good times we had during my stay on board, I hope to come back one day.

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Part I Problem introduction

1 Problem definition

As interest in climate change and other environmental issues is increasing many companies seek ways of becoming Best-in-Class or forerunners. In Europe the attention for the environment is already large and growing exponentially, but in other parts of the world attention for this is emerging. Furthermore, companies are currently discovering sustainability as an economic opportunity.

An important aspect in environmental issues are air emission such as Carbon Dioxide and other greenhouse gases and gases that are harmful to public health such as Sulphur Oxides, Nitrogen Oxides and Particulate Matter. Although considered a rather clean industry, because responsible for relatively low greenhouse gas emission per volume of transported material, the shipping industry is an important polluter of other gaseous emission, such as NO_x and SO_x. Until recently, little action had been taken to realize reductions, not by governments or industry.

Today, actions seem to be everywhere. After road and air transport, governmental and public focus is shifting to shipping and the industry is taking its responsibility and anticipating on future developments and legislation [1].

Another important development is the increase of fuel prices. Fuel costs are already between 25 and 50 % of vessels' variable costs and there is no prospect for stabilization of the prices as long as there are no viable alternatives for fossil resources.

This research explores the major causes of fuel consumption by dredging vessels and aims to design a technique to reduce CO_2, NO_x and SO_x emission while at the same time reducing fuel costs.

Dredging is big business in multiple ways, the ships are enormous and the displacement of ground material has large influence on the environment. This might lead to the conclusion that emission cannot be avoided and that trying to reduce them would be a 'drop on a hot plate'. On the other hand because proportions of vessels and quantities of feedstock are so large, a small result compared to what is still going on, could still mean large improvement.

1.1 Royal Boskalis Westminster NV

Like other companies the company Royal Boskalis Westminster is looking for opportunities to improve its environmental performances. The company acquired the ISO 14001 certificate for their environmental management system. ISO 14001 is appreciated because of its ability to enable a company to "identify and control its environmental aspects" so it can meet its environmental obligations [2].

Although embraced widely in industry over the recent years, a large heard critique to this system was that ISO 14001 puts in place little actual demands within a company. "ISO 14001 requires firms only to put in place the systems or structures for monitoring environmental aspects and reducing environmental impacts. There is no requirement that environmental performance actually be improved or that specific goals be met. In fact a firm's environmental performance could even deteriorate while the firm is certified"[3]. The 2004 update of ISO 14001 does specify an obligation for continual improvement [4], it also specifies that "objectives and targets should be specific and measurable wherever practicable. They should cover short- and long-term issues."

What actions can Boskalis take to comply with ISO14001 requirements and actually make a difference? Until now objectives have been just general. Boskalis has specified its own goal to take ISO 14001 to a higher level by not only setting objectives of becoming more sustainable but actually realizing them. To realize (part of) this objective the interest rose at Boskalis to change their working methods in order to reduce the emission of the fleet; this research aims at contributing to developing novel working methods that have less negative impact on the environment.

1.2 Objectives of dredging industry

To identify the situation in which emission affect the dredging industry it is helpful to get more insight into the objectives of a dredging company. Figure 1 shows the objective of a dredging company in a schematic way: an objective tree. In the tree, the top level shows the key objective. The lower levels show the breakdown of this objective in different sub-objectives. The company's key goal is to achieve a sustainable market position. This means optimizing the current market position but also securing it for the future. On the first lower level this goal is divided into an economically sound business and a good reputation. The sub goals of the good reputation are minimization of negative social and environmental impact. In this way the three pillars of sustainable development theory People, Planet, Profit (three P's) / Social, Environmental, Economic are respected [5].

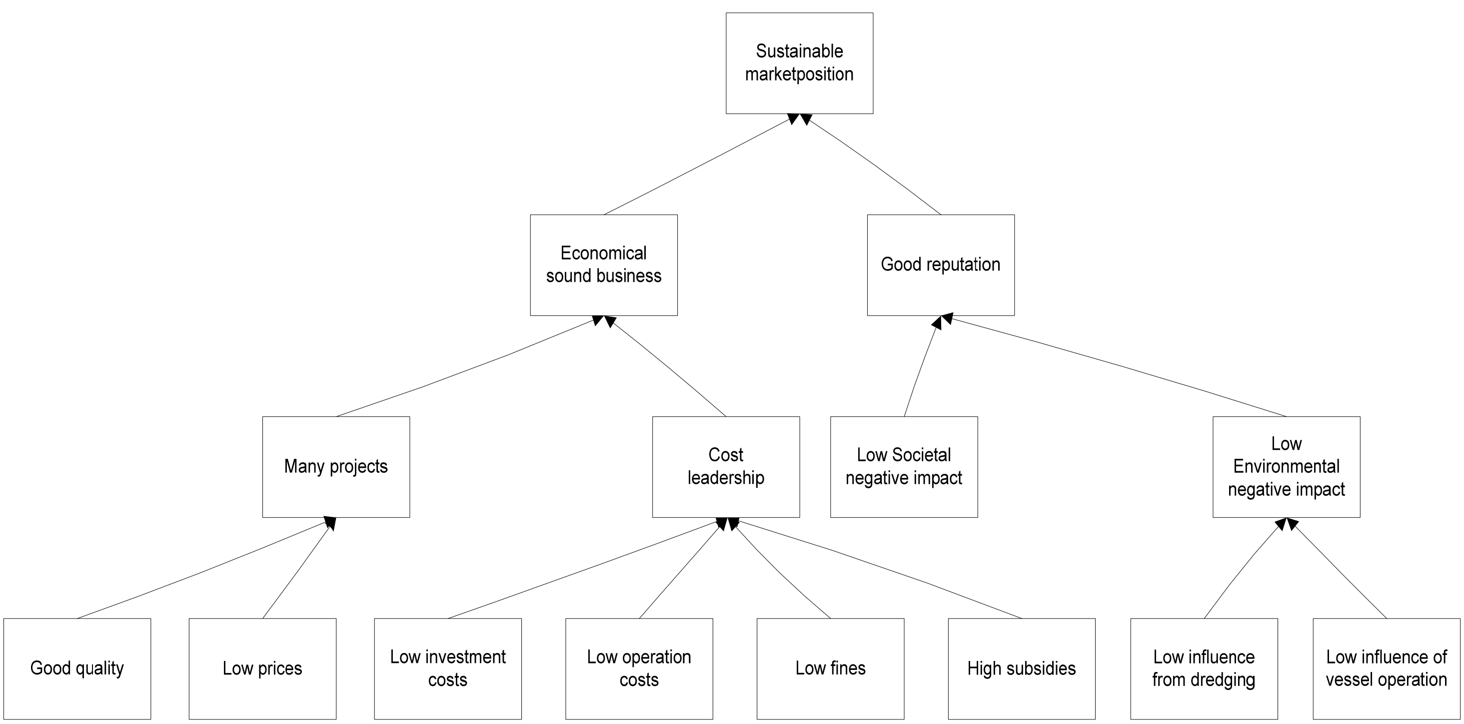


Figure 1-1 Objective tree dredging company

Reality usually shows that it is difficult to equally respect all three pillars of sustainable development. For companies the economic interest is often dominant over the other two. Plans to respect society and the environment are often made, but when the economic situation suffers they will soon be withdrawn. This is equally true for a dredging company and therefore the economic pillar receives more weight in the company than the good reputation. The perfect balance between economy and reputation is unknown, also because these factors are interrelated; good reputation is equally responsible for the generation of income. Fact is that both factors need to be present to achieve a sustainable market position.

1.3 Research objective

This research aims at helping dredging industry achieve its objective of a good reputation while making sure a minimum of extra costs will be required. This is in line with the three P's; the good reputation is acquired because environmental and social impacts are reduced and the economic goals are not forgotten. The expectation is that when dredging projects are considered sustainable because they are performed with less emission, the contractor will have an advantage in comparison with its competitors in tenders and therefore acquire more projects.

More specifically, the objective of this research is to define an approach aimed at reduction of the amount of gaseous emission in an economically feasible way. A more innovative operation process is designed to secure cost leadership.

1.4 System boundaries

In the previous paragraphs we have seen that the problem addressed in this research is the pollution caused by the large amount of emission from dredging ships, the objective is to reduce emission. This chapter will further elaborate on the problem and define the boundaries of the system that will be considered in this research.

To define the area of research it is important to formulate system boundaries. This research is bounded on four levels:

1) The type of emission considered are gaseous emission, CO_2, NO_x, SO_x
2) The method of abatement considered is fuel reduction by operations management
3) The solutions focus on the existing dredging fleet
4) The type of system designed is a soft system

The rationale for the choice of these boundaries is discussed in the following paragraphs. Factors outside these system boundaries will not directly be included in the analysis or design of this research.

1.4.1 Type of emission

In Chapter 2 Technical Perspective an overview of categories of emission of a vessel will be given. Because of limitations in time and scope it is impossible to investigate the complete list. Different emission would require completely different methods of research. Considering current developments in regulations and public opinion the choice has been made to focus on air emission, in particular: CO_2, SO_x, and NO_x. Furthermore, expectations are that improvements are possible for gaseous emission, since not much effort has been invested yet in their prevention.

The CO_2 emission from the shipping industry vary between 2% and 3% of the world's total level of emission (dependent on what source is used [6]) while being responsible for the large majority of all goods transport worldwide. This relatively small percentage of greenhouse gas emission provides a strong argument to promote shipping in terms of global ecological footprint [7]. Nevertheless shipping does not hold a good environmental reputation; it is not hard to imagine that people who see a big, dirty, smoking ship do not really have the idea that this relates to an environmentally sound industry. Additionally: can it not always be better? If an industry is little polluting this does not necessarily mean that there is nothing to be gained.

Transportation is a highly competitive market. Making the shipping industry more sustainable could make a positive difference to its market position. Thus decreasing pollution will be good for business and this will reflect on dredging as well. Within the dredging industry the reduction of emission could increase the market share of individual companies due to outperforming the competition; but it can also benefit the sector as a whole if it is considered as an industry having a less negative impact on the environment.

Concerning emission of SO_x and NO_x the share of the shipping industry is more substantial and proportionally growing because of considerable reductions realized in other industries. Numbers vary around 15-17% for this share [8]. The European Commission expects SO_2 emission from ships in European waters to account for 75% of all emission on EU territory-based sources by 2010 [9].

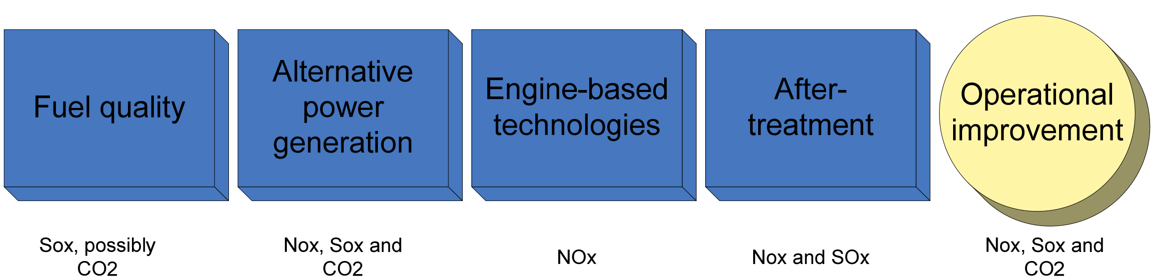
1.4.2 Methods of abatement

A reduction of emission can be realized in several ways. First of all there is the traditional engineering solution where for each humanly created issue a technical tangible artefact is designed which is supposed to solve the problem. However effective the prior approach may be, solutions can also be highly expensive, take a long time to implement and have undesired side effects on the complete system that require more new solutions.

Several methods are available for the reduction of emission. For this research the methods have been summarized into five categories. In the table below the categories and the type of emission they have a positive effect on are listed:

1. Fuel quality (abates SO_x and possibly CO_2)
2. Alternative power generation (Fuel Cell, Shore side power) (abates NO_x, SO_x and CO_2)
3. Engine- based technologies (abates NO_x)
4. After-treatment (NO_x and SO_x)
5. Operational improvement (abates NO_x, SO_x and CO_2)

Table 1-0-1 Categories of abatement methods



The categories in the blue blocks in Table 1-0-1 require technical artefacts: changes in technical installation or fuel. The yellow circle represents the category which requires changes in human behaviour.

As described above there are many possibilities for technical artefacts that could reduce several types of emission. When building new ships it is wise and possible to investigate the possibilities of integrating some of these artefacts into the design. On the other hand the life expectation of a vessel is around 30 years. Therefore, many of the existing ships will still be running for a long time, with their polluting engines running on fossil resources. Retrofitting is sometimes possible but often expensive, not because of material and labour costs but more so for cost of lost operation time.

This research focuses at how reductions can be realized on the existing fleet without a need for retrofitting. Therefore, operational improvement is the considered method in this research. The solutions can be implemented directly on the existing fleet and can even have a positive effect on company costs. In chapter 2 the selection of this abatement method based on multiple criteria is explained further.

The fact that solutions in this research are designed for the existing fleet does not mean that the results cannot be applied to more technically advanced vessels in the future; they are merely one option in a wide range of possibilities. The changes in operations management can be applied in combination with other solutions or on further developed vessels in the future. Results are easy wins that will not lose their potential when applied to other vessels.

1.4.3 Soft system

The products from this thesis will be a spread sheet model to calculate the effect of changes in operations management and a set of recommendations about how to realize such changes in the company. These two products are intangible artefacts; this does not mean however that they are less effective. The advantage of such a 'soft' system [[10]] is that measures can often be taken on a short term basis and without large investments in equipment. The disadvantage can be that the implementation of such an artefact requires changes in human behaviour which might be harder to achieve.

1.5 Introduction to Technological, Institutional and Process perspective

In this research the problem situation is analyzed from three different perspectives; the technical, institutional and process aspects of the problem will be considered. In Part II Problem Analysis these three aspects will be discussed in individual chapters.

The technical aspect describes the technological background: the possibilities of the equipment, natural and human resources. It searches for possibilities of influencing and calculates which way of using the resources will result in the most desirable consequences.

The institutional aspect describes the network of institutions affecting the subject. It is important to consider the institutional environment of the problem to make sure designed solutions are legally possible but also that they are recognized as effective solutions within the institutions.

The process aspect of this research considers the process of finding solutions, choosing the right ones and implementing them in a company with many actors: persons, groups and networks. All actors normally have the companies, but also their individual interest at heart.

A healthy balance between the three aspects provides a research that not only considers technical possibilities but also pays attention to the consequences of and possibilities for influencing external factors, which will make solutions technically, environmentally and economically feasible.

1.6 Research questions

The objective of this research is to reduce the amount of gas emission (CO_2, SO_x, NO_x, PM) from sea-going dredging vessels. To reach this objective the following research question has been formulated:

How can the emission of gases (CO_2, SO_x, NO_x, PM) be reduced by operational improvement in a technically, economically and socially feasible way?

To answer this question a number of sub-questions is formulated:

1) What amount of gaseous emission does the fleet produce?
2) What are the consequences of emission of the fleet?
3) What factors can be identified to influence the amount of emission?
4) How can operational improvement influence the factors to change the amount of emission?
5) What types of organisational changes are required within a dredging company to implement operational measures, aimed at reducing the amount of emission?

1.7 Research methods

Different research methods have been applied to answer the research questions. These methods have been used in sequential and cyclical order. The methods are:

- Desk research
- Interviewing
- Measurements and experiments on board vessel
- Modelling
- Optimization

1.7.1 Research at Royal Boskalis Westminster nv

To answer the research questions a study was done at Royal Boskalis Westminster nv. All five research methods were used within this company. Boskalis is one of the largest dredging companies in the world and aims to be forerunner in both dredging technique and environmental awareness. Experiments were carried at one of Boskalis largest dredging vessels "The Queen of the Netherlands".

1.8 Products of research

This output of this research consists of two products:

- a quantitative spread sheet model which gives insight into the effect of changes in operations management on fuel consumption and emission of dredging ships.

- a framework with guidelines on which changes are most recommendable and how the company could integrate these changes in its operations management into its business.

1.8.1 Quantitative model

The first product is a quantitative model to analyze and influence the emission of the fleet of Boskalis. The Boskalis trailing suction hopper dredger 'Queen of the Netherlands' (usually referred to as The Queen) is used as pilot ship for this model. This ship has been chosen because it is not too young, nor too old, reasonably modern and of substantial size. The case study will be used to develop the model. Before the model can be used company or industry wide it will need to be validated on different ships. If the model is only validated with data that were used to develop it, the validation will have a positive outcome while the model might not be universally applicable.

The model can be used as a supporting tool to show management and staff what the result of actions in operational functions can be. As shown in the objective tree of figure 1-1 the economic aspect is essential within the company. The best way to convince company staff of the use of certain measures is to show in a quantitative way which cost reductions can be realized. Because of this mindset it can also be desirable to quantify less tangible variables as for instance 'good reputation' to show that improving this can have a positive effect on the financial result of the company.

The advantage of running simulations with a model is the ability to perform experiments on the system and find out what the influences of changes in the variables are on the performance indicators without having to actually test in real life. Operation time is highly valuable so may not be wasted. Additionally, because a simulation model creates possibilities to show numerically what the results of specific actions will be, it makes it easier to gather support for environmental measures within an industry where the economic pillar is dominant as described in the objectives.

1.8.2 Framework of guidelines

The second product is a framework consisting of guidelines and recommendations. The guidelines that will be formulated might be compared to those of 'Het Nieuwe Rijden' [[11]]. In this Dutch government campaign a number of guidelines and recommendations has been formulated that give regular car users an idea of how they can use their car in a less polluting way.

The second aspect of this framework is a set of strategic management recommendations of how a dredging company could integrate the new type of operations management into their line of work. Because of the limited time span of this research these recommendations will be fairly general.

1.9 Report structure

To provide the research and report with structure the five steps of Verschuren and Doorewaard (intervention cycle) for practice-oriented research have been followed [[12]]. Verschuren and Doorewaard define these steps as if a research project should be part of only one of these steps. However, all steps are sequential and should be considered as a cycle since after evaluation it often turns out the issue has not been solved completely and the process needs to start again. To provide a complete solution this Master Thesis Project completes the whole cycle and treats all five steps:

1) Problem finding
2) Diagnosis
3) Design

4) Intervention
5) Evaluation

This report consists of five parts: I) problem introduction, II) problem analysis, III) Case Study Boskalis IV) Design and V) Evaluation. The five parts correspond roughly to the five steps above. Part I Problem introduction identifies the problem and sets boundaries for the research. In part II and III the problem situation and its environment are analyzed further to set a complete diagnosis of system factors (causes and consequences), that are summarized into a system diagram. It provides an overview of the amount of natural resources the ship uses and air emission the ship has for its operations. These results are used to answer sub-question 1 and 2: the consequences of the system and the possibilities for influencing the consequences.
In part IV the design (step 3) is made by establishing a model which is able to calculate the values of performance indicators in different circumstances. The simulation with the model will be used to find answers to sub-question 4)How can operational improvement influence the factors to change the amount of emission? Part V Step 4 is a strategic plan for intervention within the company, the answer to sub-question 5. Finally in part V the evaluation of the project, general conclusions and recommendations for further research are presented.

Part II Problem Analysis

2 Technical perspective

2.1 Overview of emission

A dredging ship itself can be considered an independent factory with flexible location. To get a better perspective on what is actually going on inside a ship an overview will be provided of the types of emission that can be considered.

- Garbage
    - Solid
    - Sewage
    - Grey / black water
    - Scrap / Steel
- Bilge water
- Ballast water
- Sludge
- Oil and Grease
    - Biodegradable
    - Non-biodegradable
- Noise
- Light
- Gases
    - GHG (Green House Gases)
    - Other (toxic) gases
- Visible smoke
- Particulate matter (fine particles)
- Volatile Organic Compounds (VOC)

All these types of emission have their own characteristics and influences on the environment. Therefore, they all require different types of measures and analysis. Moreover, for some types of emission the regulation is very strict already, others are practically neglected in regulation.

2.2 Emission: characteristics and effects

In this chapter the characteristics and sources of the emission (CO_2, SO_x, NO_x, PM) will be described. Consequently, the impact of these substances on public health and the environment will be discussed.

2.2.1 Nitrogen Oxides (NO_x)

Nitrogen oxides is a generic name for a combination of different gases all containing nitrogen and oxygen. Nitrogen oxides are usually odour- and colourless. NO_x gases are an inevitable side effect of the combustion of oil. They are formed by the reaction of the Oxygen needed for combustion with the Nitrogen present in the air at high temperatures. The amount of NO_x formed is dependent on the combustion temperature; at higher temperature more NO_x will be formed [[13]].

NO and NO_2 are included in the Kyoto protocol: "Nitrogen oxides (NO_x = NO + NO_2) do not directly affect Earth's radiative balance, but they catalyse tropospheric Ozone O_3 formation through rapidly converting HO_2 into OH [14]."

Effects of NO_x

The main causes for concern are that "NO_x:

- is one of the main ingredients involved in the formation of ground-level ozone, which can trigger serious respiratory problems,
- reacts to form nitrate particles, acid aerosols, as well as NO_2, which also cause respiratory problems,
- contributes to formation of acid rain,
- contributes to nutrient overload that deteriorates water quality,
- contributes to atmospheric particles, that cause visibility impairment most noticeable in areas" where views know little restrictions by humanly generated objects, like rural areas or at open waters where many ships sail.
- "reacts to form toxic chemicals,

contributes to global warming.[15]"

It should be stressed that there is a substantial difference between NO_x and Nitrous Oxide (N_2O), also known as laughing gas. Where NO_x contributes to global warming by facilitating the formation of greenhouse gases; N_2O is an important greenhouse gas by itself. The major source of Nitrous Oxide is agricultural manure management, but also the combustion of fossil resources is an important contributor of the world's rising concentration [15].

2.2.2 Sulphur Oxides (SO_x)

SO_x stands for a combination of Sulphur Oxide gases from which SO_2 is the most common. "Sulphur is prevalent in all raw materials, including crude oil, coal, and ore that contains common metals like aluminium, copper, zinc, lead, and iron. SO_x gases are formed when fuel containing sulphur, such as coal and oil, is burned, and when gasoline is extracted from oil or metals are extracted from ore [16]." The amount of SO_x that is formed during combustion depends directly on the percentage of Sulphur in the fuel. The average percentage in the on ships most regularly used fuel, Heavy Fuel Oil (HFO), is currently around 2.6% [17]. Annex VI of the International convention for the prevention of the pollution of ships (MARPOL) allows 4.5%; and for Sulphur Emission Control Area (SECA) 0.5%.

Effects of SO_x

"SO_2 contributes to respiratory illness, particularly for children and the elderly, and aggravates existing heart and lung diseases.

SO_2 contributes to the formation of acid rain, which:

- damages trees, crops, historic buildings, and monuments; and
- makes soils, lakes, and streams acidic.

2.2.3 Particulate Matter (PM)

Particulate Matter consists of a complex mix of tiny particles of solids or liquids suspended in a gas. The composition of PM depends on its specific source. From fuel burning in marine engines the most important compounds are sulphuric acid and nitric acid, which originate directly from the reaction of SO_x and NO_x with air. This process is called nucleation: the process of forming particles from a purely gaseous precursor phase. Since most particulate matter originates directly from the SO_x and NO_x production this category will no further be treated separately in this research.

PM is also referred to as aerosols: microscopic airborne particles or droplets. The US Environmental Protection Agency (EPA) separates the PM from aerosols, calling aerosols "substances stored under pressure and then released as a suspension of particles in air[[18]]." This report also states the cooling effect of aerosols because of their capacity to reflect radiation.

Effects of Particulate Matter
The particles are so small that they can penetrate into the deepest areas of the lungs and cause health problems in that way. The problems that the particulates have been found to cause include:

- "Premature death;
- Respiratory related hospital admissions and emergency room visits;
- Aggravated asthma;
- Acute respiratory symptoms, including aggravated coughing and difficult or painful breathing;
- Chronic bronchitis;
- Decreased lung function that can be experienced as shortness of breath; and

Work and school absences [[18]]."

2.2.4 Carbon dioxide (CO_2)

Carbon dioxide is an odour- and colourless gas that exists everywhere in nature. Additionally CO_2 is formed at the combustion of fossil resources when the Carbon in the fuel reacts with the Oxygen needed for the combustion.

Effects of CO_2
The part of the worlds CO_2 concentration, produced by humanity, is the most important gas in terms of quantity, which is presumed to contribute to global warming. Carbon dioxide is responsible for the greenhouse effect; without this phenomenon there would be no life possible on earth. The current increase in concentration on earth is presumed to cause the enhanced green house effect and in consequence the increase of temperatures on earth. Except for its effect as a green house gas, CO_2 has no further negative effects on the environment or human health as long as concentrations remain low (current average: 380ppm).[a] The most important consumers for CO_2 are trees and other vegetation, but currently techniques are being developed for underground sequestration.

Other gases have influence on global warming such as Nitrous oxide (N_2O), Methane (CH_4) and water vapor. The effect that the different chemicals have on global warming can be indicated by the so called Global warming potential (GWP). In this scale CO_2 has value 1 where CH_4 has value 8. This means that the effect of one molecule of methane in the air is 8 times as large as that of one molecule of carbon dioxide. However the concentration of CO_2 in air is much larger which makes the total effect of CO_2 concentration on the greenhouse effect the most important.

2.2.5 Geographical effects

Air pollution is never solely a local problem; all gas emission can be transported by wind over large distances but there are substantial differences. Where PM, SO_x and NO_x predominantly have effects on relatively short distances up to about 500 km from the source, green house gases have effect on a global scale. Sulphur from SO_x that comes into the air and causes acidification will cause no problem in open sea areas because it will rain down at sea before it can reach coastal areas. Particulate Matter produced at open sea will have dissolved in air to a low concentration when it reaches land and will no longer cause respiratory problems.
Carbon dioxide on the other hand is a global problem. For the worlds' total carbon dioxide content – which partly determinates the force of the green house – there is no difference between emission generated at open sea or within a dense populated port area. The effects of these characteristics are visible in legislation, which will be elaborated on in chapter 4.

2.3 Causal effect diagram

The propulsion of a dredging vessel by using fossil fuels is a large system with many different aspects. To be able to analyze whether the performance of the system will improve after intervention the current performance needs to be known. To learn more about what influences the performance indicators and how they can be changed by the problem owner an analysis of the causal relations has been performed.

In Figure 2-1 the relations between the different emission and their sources are shown in a causal relations diagram.

A negative sign indicates that the second parameter will increase if the first parameter decreases. A positive sign indicates that the second parameter will increase if the first parameter increases. A question mark indicates that the relation is unknown at this moment and needs to be researched more thoroughly.
Different types of factors can be identified in the diagram:

- The blue ovals represent steering variables, these are variables that the operations management has control over, so is capable to change.
- Yellow variables are (environment) or circumstantial variables. This means that their values influence the outcome of the system without the possibility for the problem owner to interfere.
- White variables are system variables. This means that these variables form a transfer step between steering or environment variables and performance indicators.
- The red ovals represent a special type of system variables namely the different types of gaseous emission.
- The grey factors are performance indicators that are extracted from the dredging contractors' objectives in Figure 1-1.

The causal diagram of Figure 2-1 shows that the system is complex [[19]], this means the system consists of different interrelated factors. Because of the interrelations of the system it is impossible to know the exact outcome of the performance indicators without further research. An example of an unpredictable relationship is the SO_x versus CO_2 relation: to comply with new Sulphur Emission Controlled Area (SECA) regulation, fuels need to be desulphurized; this process requires energy and additional crude oil which causes an increase in the CO_2-production of the system [20] [21] [22].

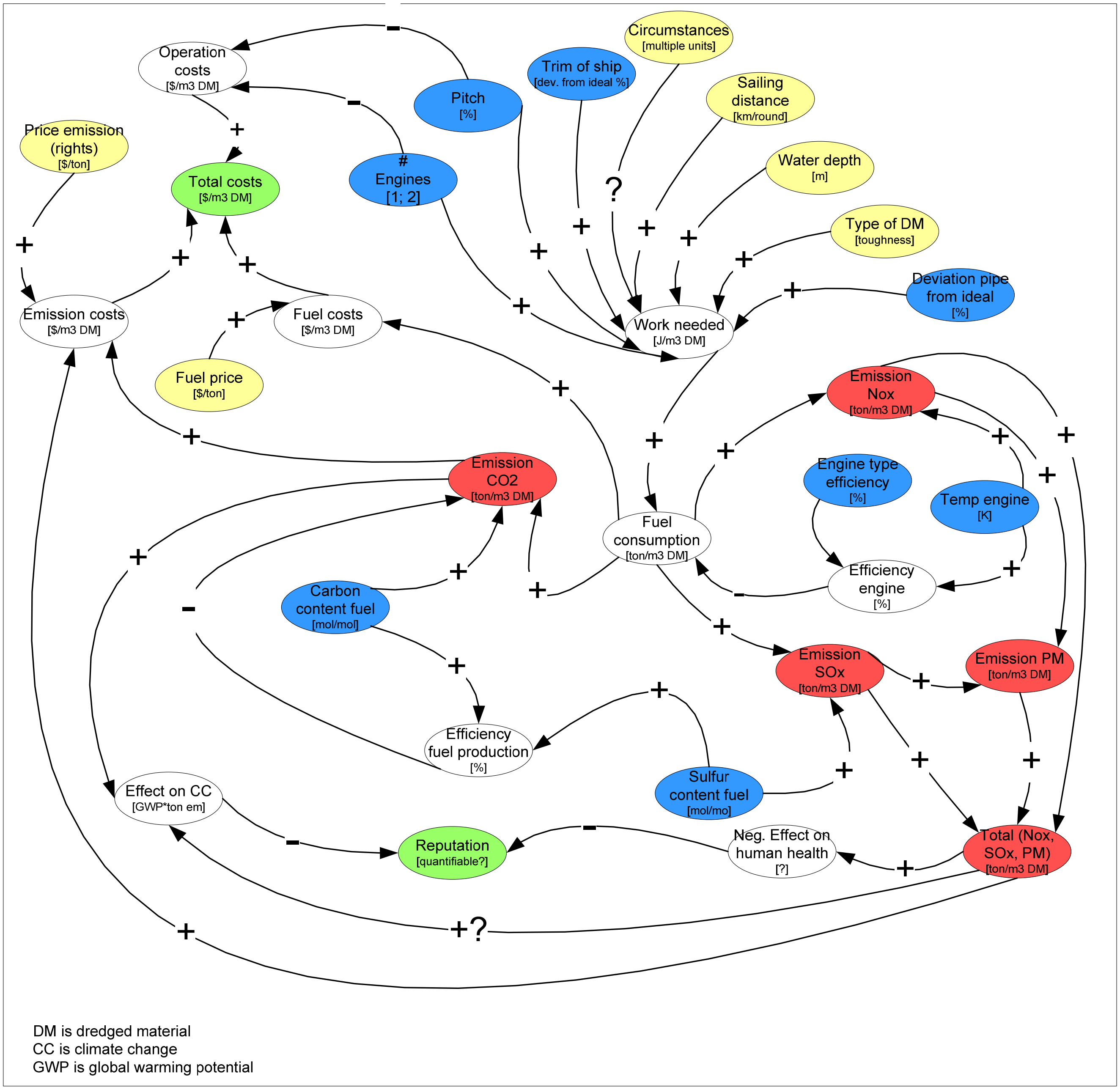


Figure 2-1 Causal effect diagram of system operation of dredging vessel

2.4 System diagram

After the causal relations in the system have been identified it is helpful for better overview to organize system by category of variable; to do so the factors first have been sorted by type: steering variables, environment variables, performance indicators and system variables. After this the system variables have been sorted with comparable peers to form subcategories. The result of this sorting phase can be found in Figure 2-2.

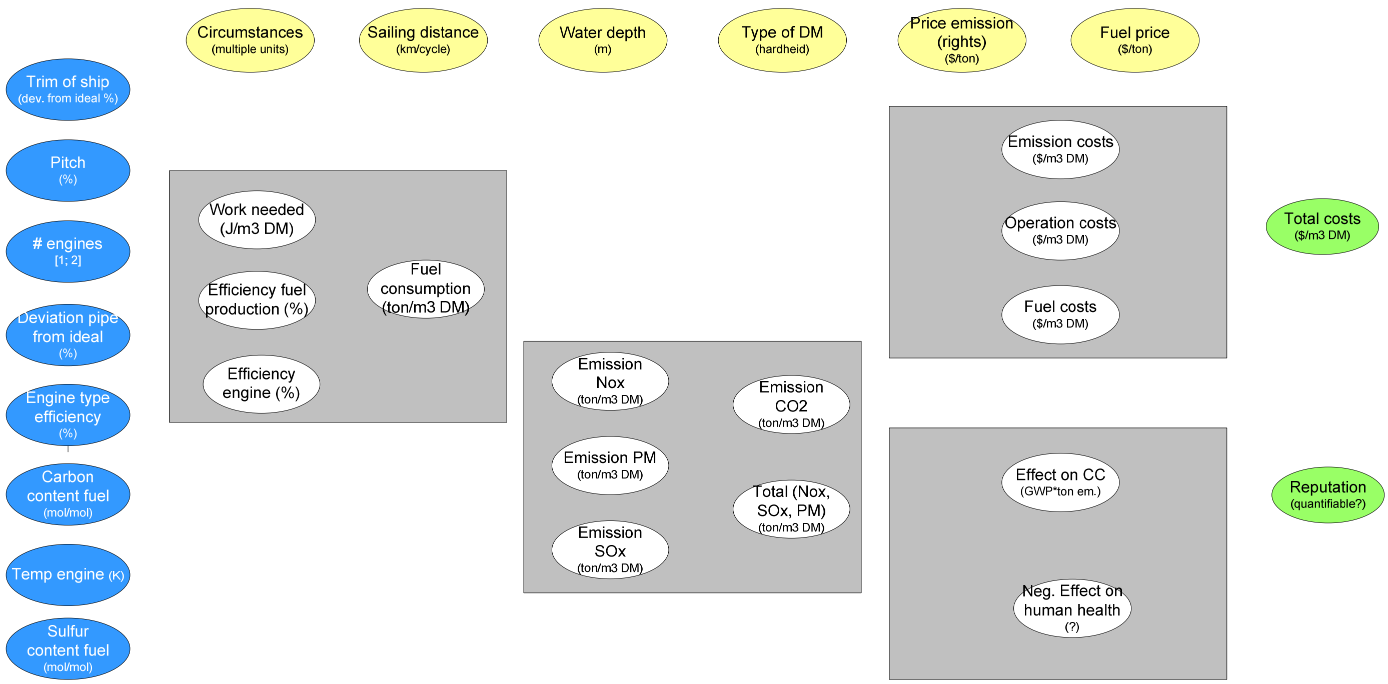


Figure 2-2 Transition phase from causal to system diagram of system operation of dredging vessel

Four types of subcategories system variables have been identified inside the system diagram:

1) Fuel consumption
2) Emission
3) Impact on profit
4) Impact on people and planet

The way the four categories influence each other in the systems diagram is visualized in Figure 2-3. The category 'Fuel consumption' enters the category 'Emission' from above which means that this is an environment variable for the amount of emission. The emission can be influenced indirectly through a number of steering variables that change the fuel consumption. Moreover, there are also steering variables that have a direct impact on the amount of emission. The purpose of this diagram is to provide an overview of factors. It should be stressed that the system diagram is not an activity diagram; it does not consume any resources. The diagram is exclusively used to provide an overview of variables.

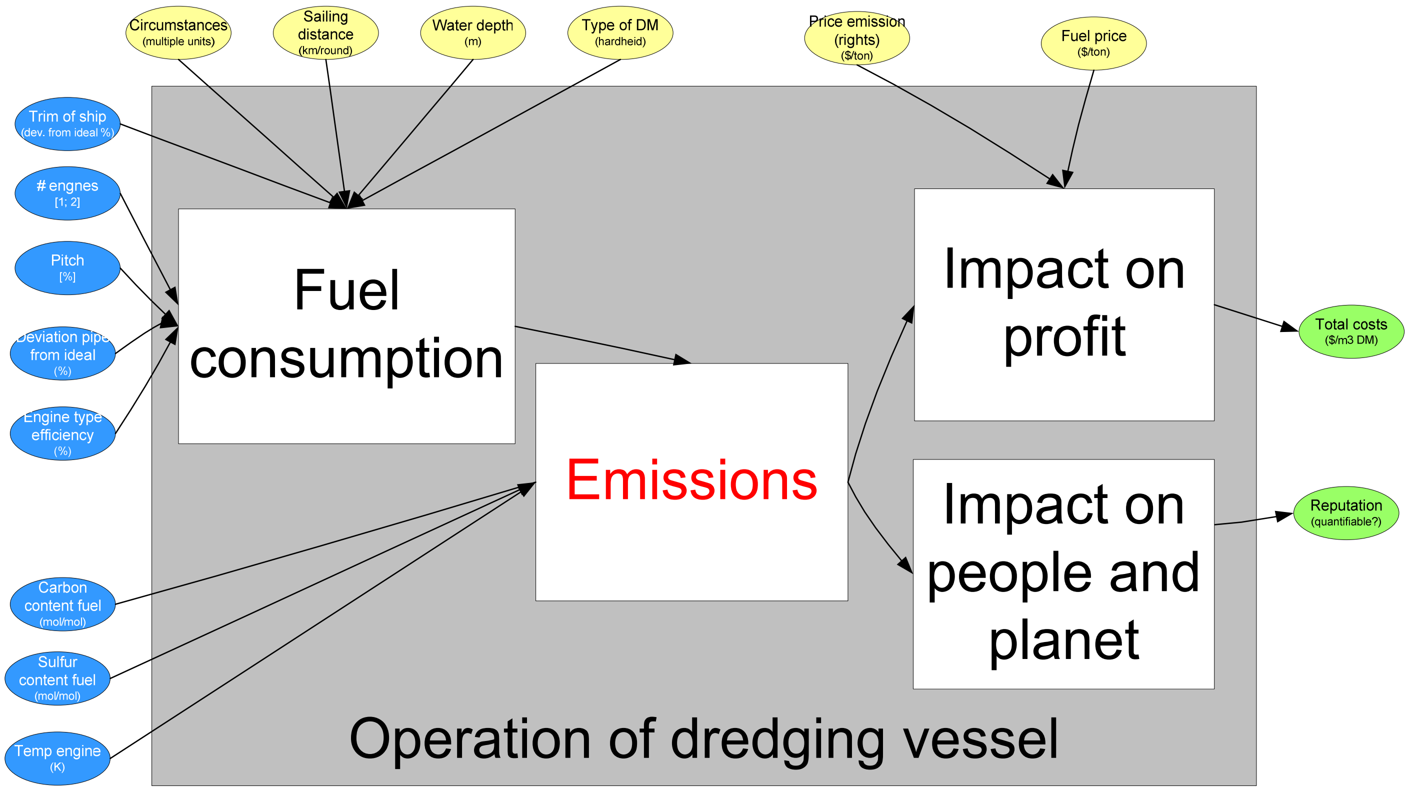


Figure 2-3 System diagram of operation of dredging vessel

2.5 Measuring

To be able to reduce emission it is important to know how much emission are actually produced during the dredging cycle (sub research question 1). This chapter describes how the amount of emission can be measured.

2.5.1 Measuring emission

At this moment there is no generally available technology for the actual measurement of emission onboard ships. There are some types of exhaust gas analyzers available, but nothing directly applicable on ships. There are assessment techniques for NO_x and Particulate Matter available by using field measurements [[23]]. TNO has developed techniques where a car drives next to a ship in port areas and is able to analyze the exhaust smoke. Also there are recent developments for a technique that provides real time available results for PM and SO_x [[24]]. At this time there is not yet one proven technique implemented in industry; costs are high and none of these techniques offers real time results. Measurements are always instantaneous and with large time gaps between series. Direct results are required to monitor the effects of changes in operations management. The time limits and equipment for this research make that it is not possible to install real time techniques.

Another important problem relating to measurements is that it is often hard to distinguish the emission from ships from the emission of land-based sources such as road traffic or industrial facilities. For these reasons in this research the amount of emission produced needs to be determined in another way.

2.5.2 Measuring fuel consumption

An alternative method to determine the amount of emission produced by a ship is to measure the fuel consumption of the ship. Most emission are directly related to the amount and specifications of fuel consumed. When the fuel consumption of a vessel can be determined the amount of emission can be calculated from these values. For SO_x and CO_2 the emission can be determined directly based on fuel consumption and fuel specifications. The NO_x emission are dependent on more factors such as combustion temperature.

There is a deviation between the interests of policy making/regulating parties and private shipping companies, when considering the time and method of measurement. To a shipping company there is no added value to measure the emission of SO_x and CO_2 after combustion. For a ship operator it is just as easy to measure the fuel consumption, also because in that way they can make sure to only measure the emission coming from the ship itself without interference from other sources. Additionally it will also give the ship operator direct numbers about fuel savings and related cost reductions.
For a regulating party, on the other hand, it is important to have quantitative numbers of the amount of air pollution. There are multiple grounds for this dilemma. First of all, the objective of policy makers is to lower the total amount of air pollution. Regulators are usually assigned to determine what the concentration of a certain gas in the air is. Furthermore the objective of policy makers is usually to limit the concentration of a certain emission. Policy makers are not interested in how much resources were consumed but want to know what the influence of the ship was relatively to the surrounding air quality. For this reason research done by a private shipping company will be different from research by governmental institutions.

In this research the data about emission will be derived directly from the data about fuel consumption. Appendix E provides an overview of the theoretical basis for deriving emission from fuel consumption.

Wang et al. [25] argue that a fuel based method is inferior to an activity based method because of inaccuracy. Since there is no available alternative at this moment, there is no other choice in this research. However, this point will be considered when deciding on the reliability of the results and when planning future research.

2.6 Available abatement solutions

This chapter provides an overview of available solutions to lower emission and elaborates on several of them. Eventually the choice is substantiated for researching the influence of operations management further in this research.

2.6.1 Overview of emission abatement methods

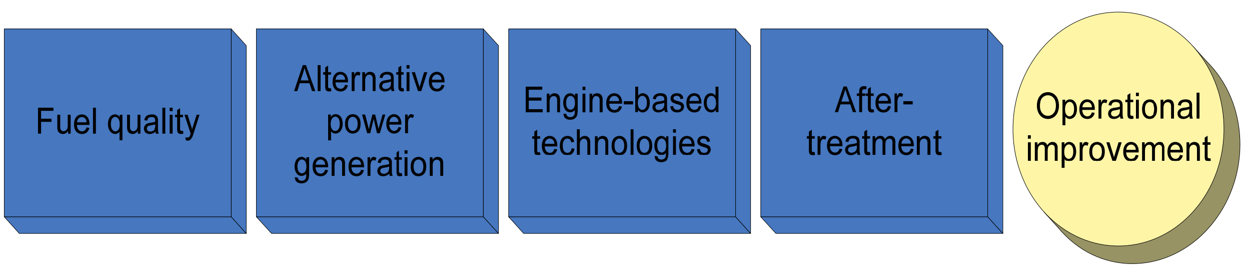
For the reduction of NO_x there are quite a few technologies available at this moment and others are being developed. However, these solutions all have a loss of engine efficiency as undesired side effect. For SO_x, stakeholders are also trying to develop solutions but like the NO_x abatement technologies they all cause a loss of efficiency.

The only solutions effective on CO_2 emission are an increase of efficiency or a change of combustion method. All NO_x and SO_x reduction methods currently available have a negative influence on the overall efficiency of the system and therefore produce only more CO_2. Technically, capture of CO_2 is possible but it would cause practical problems in shipping. CO_2 would need to be stored temporarily on board a vessel and the constantly changing locations would require a world infrastructure to collect and store the material. This infrastructure will certainly not be available on short term basis.

An overview of possible solutions for the maritime sector is provided in the report of Mohan 2007[[26]]. Mohan provides an extensive list of different types of solutions available for container ships but applicable much wider in the maritime industry. Emission of CO_2 is mostly left out of consideration in Mohan's thesis. The complete report of Mohan is viewed from the perspective of port authorities, methods of abatement and incentives for ship owners from operations management on board ships is not discussed. Mohan categorizes the available technologies in (I) Pollution prevention, (II) Pollution Control, (III) End-of-pipe technologies, (IV) Port's abatement technologies.

For this research the different solutions have been categorized into the following five categories:

6. Fuel quality (abates SO_x and possibly CO_2)
7. Alternative power generation (Fuel Cell, Shore side power) (abates NO_x, SO_x and CO_2)
8. Engine- based technologies (abates NO_x)
9. After-treatment (NO_x and SO_x)
10. Operational improvement (abates NO_x, SO_x and CO_2)



Emissions	SOx, possibly CO2	NOx, SOx and CO2	NOx	NOx and SOx	NOx, SOx and CO2
Adjustments	Limited	New built	Retrofit / new built	Retrofit / new built	None
Implementation time	Short	Long	Middle	Middle	Direct
Costs	Middle	High	Middle	Middle	None

Figure 2-4 Multi-criteria comparison of categories of abatement methods

In this research the port's perspective is replaced by the perspective of a (dredging) ship owner that has control over operations management. Categories 1 and 2 are similar to Mohan's Pollution prevention, 3 is Pollution control and 4 is End-of-pipe technology.

2.6.2 Operational improvement

There are different methods of operational improvement of a dredging vessel that are used as a method of reducing fuel consumption. Two of those are discussed in this paragraph.

2.6.2.1 'Vessel Speed Reduction' (VSR)

The efficiency of a Diesel engine increases when speed is lower. In fact the curve of fuel consumption increases exponentially with speed. The idea behind 'Vessel Speed Reduction' has been adopted from road traffic. In order to increase safety among commuters alongside a reduction of fuel consumption, speed limits have been altered. Yet every car is a separate entity and thus there will always be speeding vehicles. The conclusion is that it is not possible to control each car drivers behaviour at all times. The same can be said for international shipping. Regulators will never be able to track the actions of every single ship [26]. In order for the system to work ship owners will need to have their own motivation to reduce vessel speed.

Examples of VSR programs in the world
In several places there are VSR programs in action intended to realize a reduction of air pollution from gas emission. Most projects from authorities are aimed at emission in port; but within the shipping industry there are clear trends of 'Vessel Speed Reduction' on long distances to cut fuel costs as well as emission [22]. In this paragraph four examples of VSR situations are described:

At the Port of Long Beach, California, USA the Green Port Policy of 2005 describes the voluntary request to companies to lower their speed: "Vessel Speed Reduction (Green Flag Program) – is a voluntary, incentivised program requiring ships to slow to 12 knots at a distance of 20 miles from Point Fermin (Port entry point) [27]."

At the Port of Rotterdam in The Netherlands there is no special program in action for 'Vessel Speed Reduction' at this date[28]. The Port of Rotterdam states that the main reasons for the absence of such a program are considerations of safety of the vessels. As Mohan [26] fraises it: "A VSR program is in place in the Port of Rotterdam but this is for safety reasons not environmental." There are, however, recommendations for a program to take back speed to coordinate sailings with harbour capacity. By taking back speed to adjust expected arrival time to the time that the vessel is required to be in the port area a vessel can prevent to needlessly spend time in port.

The Holland America Line (HAL) cruise ship company introduced a 'Vessel Speed Reduction' program several years ago [29]. At HAL a ship can for instance leave one hour earlier and arrive one hour later in the port and therefore reduce its sailing speed at sea. A special team is assigned with the task of searching for the optimal balance between vessel speed, emission and time in port. This is a complex balance with many interrelations, like the costs of port time but also the appreciation of guests to have time available for excursions ashore. Regardless of this delicate balance, 'Vessel Speed Reduction' for a cruise ship company is a relatively easy task. Since part of the objective of cruise ship guests is to sail, be entertained and sleep on board the ship; spending some extra time on sea will not necessarily mean a loss of income as it would for a container or dredging ship.

In Dutch industry an increase can be seen in the amount of attention paid to this concept. The "Platform Scheepsemissies [30]" founded by several parties in Dutch industry has "Control (Beheersing)" as one of its themes and organized a seminar about fuel reduction in November 2007. Within the platform, companies can acquire information and share experiences about saving fuel by 'Vessel Speed Reduction' next to other concepts like weather monitoring and optimization of sailing routes.

2.6.2.2 Vessel trim

Theoretically the trim and ballasting methods of a ship can have large influence on the fuel consumption. The trim of the ship can be influenced by the way it is loaded. At Wagenborg Shipping streamlining trim and ballasting has been implemented successfully to reduce fuel consumption. From their experience a vessel with the same power and therefore fuel consumption can sail up to 0.5 knots faster when streamlined optimally [31]. On the other hand, other companies that performed tests experienced that it is very difficult to separate the exact influence of the right trim from exterior variables. The results Wagenborg Shipping achieved in this matter have been purely based on field experiments.

On dredging vessels the loading method of the ship is already monitored closely to fill the hopper as much as possible. This action returns each cycle, realizing the ideal trim each dredging phase would take a lot of time. This opposed to a container transport company like Wagenborg where the loading of the ship can be calculated extensively. When loading a dredging vessel one minute of reduced alertness by staff can make the difference between ideal trim and non-ideal trim.

More information needs to be available before this method can be taken into consideration as random experimentation with the optimization of trim on board a dredging vessel will cause substantial time losses.

However, this method might be suitable for future research. There is a lot of human attention paid to maximizing the load of the hopper; it is possible that the final attention spent here could better be spent on maximizing the trim. Future research is necessary to investigate this trade-off. This research investigates what the required fuel consumption is per kn of vessel speed; with the results of this research it is possible to predict how much time or fuel could be saved if the top speed of the vessel were lays 0.5 knots higher due to optimal trim.

2.7 Reduction of fuel consumption by operational improvement

This research focuses on operational improvement of the dredging cycle. A possible method for this is 'Vessel Speed Reduction' as introduced in chapter 2.6.2.1. In the system diagram of Figure 2-3, an overview of possible steering variables is provided which shows where they influence the system. By influencing the steering variable "time available" the possibility is granted to design the project in a different way. An available solution for this is 'Vessel Speed Reduction'.

There are several reasons why operational improvement is chosen as subject for this research. The most important are:

- A reduction of fuel consumption has a positive influence on all emission as opposed to engine based or fuel quality solutions available that only affect NO_x or SO_x but always have a negative effect on the efficiency of the system and therefore the emission of CO_2.
- Operational improvement can be effective on immediate basis on existent ships without the need for retrofitting.
- Operational improvement can be effective on each vessel at every moment; in the future it can be equally effective on newly built vessels.
- Operational improvement can be combined with all other abatement technologies.
- Appropriate operational improvement has relatively low costs or can even be economically feasible, because of fuel bill cuts.

Reducing fuel consumption by improvement in the operational functions is a truly sustainable solution in the context of this research; it has a positive effect on all emission types and decisions are selected that assure most favourable impact on *economy, society* and *environment*.

2.7.1 Dredging time cycle

Like in most industries time is a precious factor in dredging and certainly not to be wasted. On the other hand time is not a constant factor as it is in shipping industries like container or chemical transport. Compared to a static activity like container transport the dredging process is highly dynamic with different stages of the process following each other in fast order and constantly returning. Figure 2-5 illustrates the different activity phases of the dredging process.

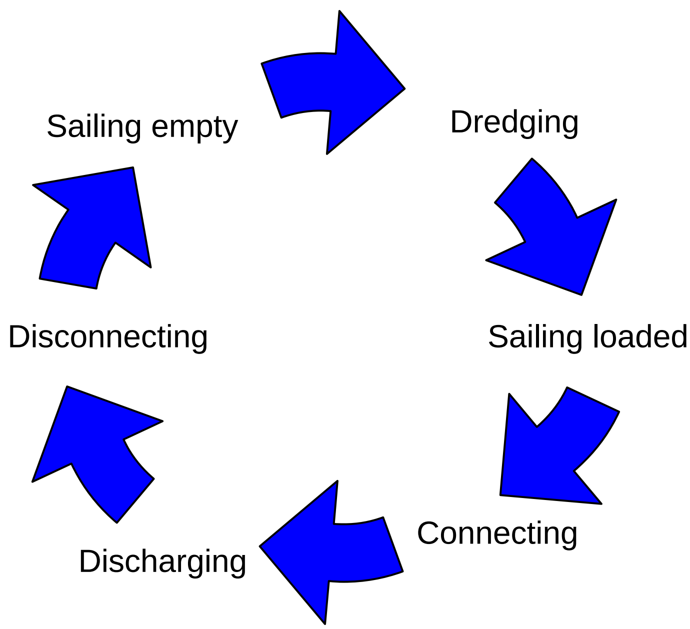


Figure 2-5 Overview of standard dredging cycle

The fuel consumption differs highly between the different stages of the dredging process. Data of Royal Boskalis Westminster NV are based on estimations and field experiments. Numbers are averages for the vessel Queen of the Netherlands, which are used for the preparation phase of tenders:

- Sailing → 3590 (l/hr)
- Dredging
    - Sand → 2680 (l/hr)
    - Silt → 2270 (l/hr)
    - Clay → 2540 (l/hr)
- Dumping → 1540 (l/hr)
- Pumping → 3530 (l/hr)

The exact duration of a complete cycle is different for each dredging project. The largest variation is caused by a difference in sailing distance between dredging and discharging area. The sailing time can vary from 10 minutes to many hours. The other phases – although this remains dependent on circumstances and type of dredged material – have a more constant duration. Dredging and discharging via pumping typically last around 2 hours, dumping takes around 10 minutes.

Fuel consumption reductions would be most effective during the activities that have the highest fuel consumption, in this case sailing and pumping. In the present situation the simple objective is to finish each activity as fast as possible. In this research the effect of not operating at maximum speed will be investigated; more precisely, the effect of doing this on the performance indicators of the company.

The several phases in the system are closely connected and follow each other in fast order. Additionally in the transition phase from one activity to another it is possible for improvements to be made; for instance, when transferring from low dredging speed to high sailing speed. Currently this change is performed at full power. With more specific information about fuel consumption during separate dredging phases, simulations can be run to calculate the consumption after changes in operations management which can provide data for better project planning.

2.7.2 Integrated bridge systems

An integrated bridge system is a computer or set of software available on a vessel's bridge that provides information to help the Officers make decisions or even provide the decision for them. Already in 1982 Van Rietschoten and Houwen which later changed to Imtech published about the possibilities of reduction of fuel consumption through operations management [[32]]. The plotter they described at that time can be viewed as a predecessor of the integrated bridge systems in development nowadays. IMTECH offers different possibilities for integrated bridge systems. An example is the decision support system DSS 3500 that helps the staff choose the most efficient sailing method. Imtech's Decision Support System 3500 (DSS 3500) is an intelligent software application to process the flow of information onboard that advices the best decision – based on predefined criteria, e.g. required arrival hour – regarding speed and course.

The Maritime Research Institute Netherlands (MARIN) is developing a software tool in an international joint industry project, Ship Service Performance Analysis (SPA) [[33]]. This software tool is destined to be used on board the ship and give the Officers direct insight into the consequences and possibilities of their actions. For inland vessels such a system the speed controlling system 'Tempomaat' is available already and the utilisation is widely promoted within the platform 'Voortvarend besparen' [[34]] initiated by the Dutch agency for sustainability and innovation 'Senter Novem' [[35]]. At this moment the project is aimed at shipping companies that make a lot of sea miles as opposed to dredging vessels that only cross the oceans a few times a year. The particular characteristics of the dredging cycle would ask for a specific version of such software which could be developed. The results of this research provide recommendations for whether it is feasible for dredging companies to step into this or a similar project for the dredging industry.

2.8 Conclusions technical perspective

The technical background of this research shows that there are many possibilities for abatement of emission that all have specific characteristics and possibilities. This research will focus on the method of reducing fuel consumption by changing operational behaviour on board. This method has been selected because it reduces all gaseous emission under consideration, is relatively cheap to implement and can be effective at all vessels at all times. It can be combined with different methods in the future on more modern vessels. The first step is the analysis of the operational behaviour on board and testing how this influences the amount of emission. If optimization of company objectives delivers a positive outcome for the method the question remains how to implement this on board. An integrated bridge system is an option for this. The next chapter analyses how this subject affects different stakeholders and their relations with each other. It specifically analyses which relations influence the process of change if an emission reduction operational system would be introduced.

3 Process perspective

This chapter describes the process aspects that affect the research problem and the range of possible solutions. Process aspects consider the set of relationships between stakeholders that together are responsible for the process of operation and change.

The chapter starts with an identification and categorization of the involved stakeholders. Secondly, it describes the different levels of operations management within a dredging company and the type of decision making that applies. Thirdly, the relations between the contractor and the other categories of stakeholders are analyzed.

Consequently, the distribution of power within the dredging company is analyzed further and the principal-agent problem that occurs when trying to improve operational behaviour. After this the relationship with a possible subcontractor is discussed and the relationship between contractor and external – outside world – stakeholders. The relationship between contractor and the stakeholder category 'Authorities' is not discussed to great length in this chapter. Chapter 4 Institutional Environment will provide more insight into this relationship.

3.1 Stakeholder analysis

The dredging contracting industry is a strong oligopoly where a few large players seem to divide all large projects available worldwide. Consequently all players are large, internationally operating companies. Within such a large multinational organisation the process to apply changes in the operational behaviour on the vessels can be deemed interactive; involving many different stakeholders and levels of decision making. Next to the different stakeholders within a dredging organisation the process also involves exterior stakeholders such as governments and affected citizens.

The key-stakeholders involved with a dredging project are listed below:

- Contractor
    - Head office
    - Project office
    - Vessel staff
- Client
    - Head office
    - Project supervisor on behalf of client
- Subcontractor
    - Head office
    - Vessel staff
- Authorities
    - International authorities
    - National authorities
    - Local authorities
- External
    - Non Governmental Organisations (NGO) (international, national and local)
    - Surrounding residents

Figure 3-1 shows a model of the different stakeholders. The pie pieces represent the different categories of stakeholders; the colour rings show their layer of influence. The outer ring represents a higher level of authority but is further removed from the action layer. The interactions of the different stakeholders are normally restricted within their pie piece and ring of influence. International authorities and NGO's speak to the head office of a contractor, the head office speaks to the vessel staff.

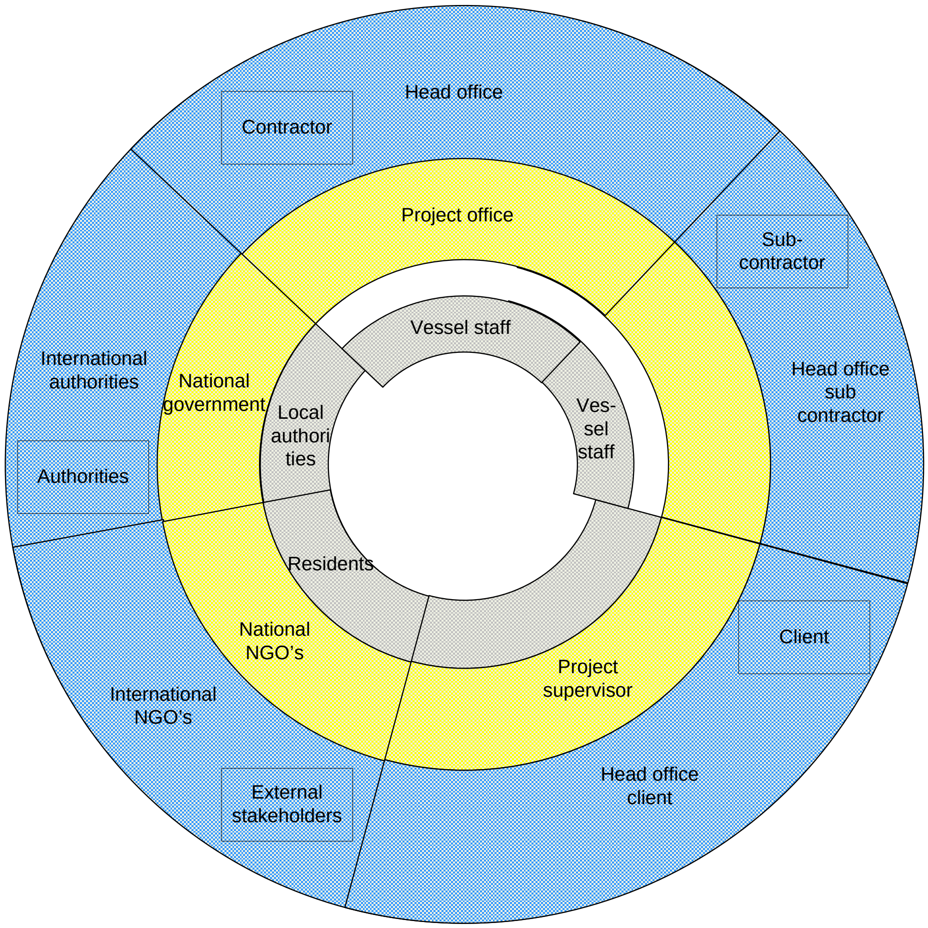


Figure 3-1 Model of Stakeholder analysis

3.2 Operations management

Different definitions are used for operations management: "Management of the conversion process that transforms inputs such as raw material and components into outputs in the form of finished goods and services [36];" "The management of systems or processes that create goods and/or provide services [37];" "The design, operation and improvement of the systems that create and deliver the firm's primary products and services [38];" "Management of main business activity: the organizing and controlling of the fundamental business activity of providing goods and services to customers [39];" "Operations management focuses on carefully managing the processes to produce and distribute products and services [40]."

To a dredging contractor the dredging cycle is the fundamental business activity; this dredging cycle provides the service of replacing material from dredging area to discharging area. In this research operations management is referred to as the organizing and controlling of the dredging cycle.

The operational function within a dredging project is divided in three levels of decision-making:

- Strategic
- Tactical
- Operational

Operations strategy is not to be confused with organisation strategy. The strategic management takes place at the departments spanning the entire organisation, where decisions about company strategy and project strategy are made. "Operations strategy is narrower in scope, dealing primarily with the operations aspect of the organisation [41]." Examples of operations strategy decisions are:

- How will the service be produced?
- Where will the facilities be located?
- How much capacity is required?
- When should extra capacity be added? [42]

To assure that operations strategy can be truly effective it is ineluctable to align it with the organisation strategy.

This research is bounded to the operations of individual dredging projects. If decisions are referred to as strategic this means they relate to operations strategy. A contractor also takes organisation wide strategic decisions such as the decision to construct new vessels or changing operation to adhere to a more sustainable policy. This level of decision-making – although it constrains the project decisions – is not addressed in this research. The operations strategy has the objective of managing the delivery of the service 'dredged material' within a project in the most appropriate way.

Within a dredging organisation operations management starts at the moment a contract has been signed. During the tender phase the project has been estimated for specific equipment and circumstances. During the operations phase this estimation can change substantially, the project operation is adjusted based on availability of equipment and other resources or changing circumstances like a different project design, construction method, customer wishes or fuel price.

Fout! Verwijzingsbron niet gevonden. summarizes the different levels of decision making, the management departments within a dredging contractor, the time horizon of decisions, their scope and level of detail. The table is based on a similar table from Stevenson [43], but has been customized for the specific situation of a dredging organisation.

The operational level refers to the organisation and decisions on board; the location, equipment and task are fixed variables. The tactical level concerns a project office that has a pre-defined location and limited set of equipment. The operations strategy level of a project lies with area and plant management within head quarters, here decision making comes close to capacity management; project and material is matched with most suitable and available equipment. Next to the capacity management the area management is similarly charged with the tactical decisions about the standard setup for the dredging cycle. The standard cycle setup needs to be aligned with the wishes of the client and sets the boundaries for the operational decisions on board.

Table 3-1Comparison of mission, organisation strategy and operations strategy (adaptation from table [42])

		Management level	Dredging organisation	Time horizon	Scope	Level of detail	Relates to
The overall organisation	**Mission**	Top	Board of directors	Long	Broad	Low	**Sustainability, survival, profitability,**
	Strategy	Senior	Plant / Area management	Long	Broad	Low	**Growth rate, market share, environmental goals**
Production / Operations	**Strategic**	Senior	Plant / Area management	Moderate to long	Broad	Low	**Product design, choice of location, choice of technology (cutter or dredger, which vessel)**
	Tactical	Middle	Project office	Moderate	Moderate	Moderate	**Employment levels, output levels, equipment selection,**
	Operational	**Low**	**Vessel**	**Short**	**Narrow**	**High**	**Scheduling personnel, adjusting output rates, inventory management, purchasing**

3.2.1 Operations research

It is important to make a distinction between operations improvement and operations research. The former is operational change to improve the systems performances. The latter is "problem analysis to improve operations: analysis of the problems that exist in complex systems such as those used to run a business or a military campaign, designed to give a scientific basis for decision-making [44]." "Operations research brings together mathematicians, psychologists and economists in teams to structure and analyze a problem in quantitative terms so that a quantitative optimal solution can be obtained [45]."

This research considers a first phase of operations research to facilitate the decision-making required for operations improvement.

3.3 Stakeholder relations within contracting organisation

As described in paragraph 3.1 the multinational dredging contractors know different levels of stakeholders within the organisation, with different authorities. This paragraph performs a more in-depth analysis of this relationship. It analyzes the competences of the parties and the interfaces between the levels.

It is important to identify which stakeholder has the power of influencing the steering variables – as described in the system diagram (Paragraph 2.4). Power is defined in this research as: "the potential for influence" [46].

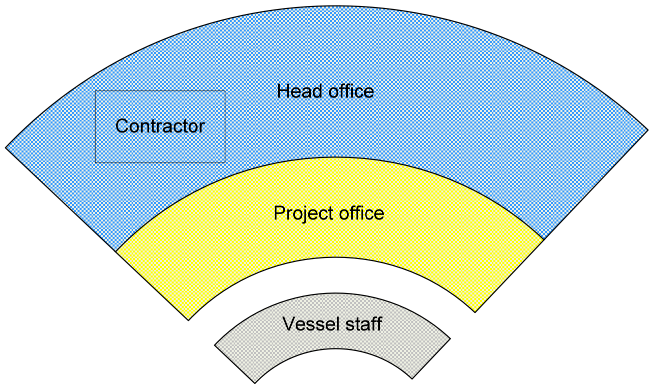


Figure 3-2 Relations within contractor organisation (part of stakeholder analysis)

In practice the Officers standing at the bridge are the direct controllers of the ship. They make the direct decision over the ships operations – control how fast a ship sails and therefore how much fuel is consumed at the end of the day – so have direct power. On the other hand, the work that these men need to perform is calculated minute by minute in the head office, which predetermines the degrees of freedom the vessel staff has. The degrees of freedom can be categorized in two types: (I) the short term decisions are the responsibility of the vessel staff – this will be called the operational actions – category (II) the overall cycle planning is the responsibility of the head office – this will be called the tactical actions.

The categories of decisions also require two types of process change. For the operational actions it is important for the vessel staff to gain insight into how much their operation influences the fuel consumption. The second type influences the tendering phase; this requires awareness in the head quarters and on all levels of the company. For the tactical actions, the head office needs to plan the project in such a way that the operational level has time and space available to influence the system, while assuring awareness, clarity and motivation with vessel staff, by providing them insight into what the results of certain handlings can be.

Because the works are planned so specifically and the degrees of freedom are limited the vessel staff tends to create its own performance indicators within the alterable they posses. Alterables are those elements of the problem which if changed have a significant effect on the identified needs and objectives [[47]]." Examples of steering mechanisms or alterables now used in operations are: the way the hopper is loaded to create more capacity, or the control of the ideal angle of the pipe with the ground. Under the current situation all these indicators are aimed at maximizing production. When results of these actions are satisfying the staff is sometimes rewarded with small gifts to show the companies appreciation.

If the objectives for the performance indicators change from maximal production to multiple objectives aimed at reaching the optimal balance between production and environmental impact of emission, the staff will be required to change their mindset. The familiar alterables will be changed and will need to focus on minimization instead of maximization. Question is if this will give the staff the same amount of satisfaction, a factor which could harm their work pleasure and might need to be compensated with personal rewards.

3.3.1 Principal-Agent theory; distribution of power

The distribution of power between the contractors head office and vessel staff is crucial in the realization of change. Project planning is done at the companies' headquarters while the actual power for action lies on board of the ships.

The relation between vessel staff and headquarters can be described using Principal Agent theory. The corporate interest represented by headquarters is the principal and the ship is the agent. As described above the project is completely planned at the main office; however, actions are realized at the ship. Headquarters depends on vessel staff to realize their goals, but the staff will also have their personal interest in mind and possibly hold hidden intentions, hidden knowledge / information, or hidden actions [[48]]. These are typical principal agent problems which require action from the principal for the control of agent behaviour. In the following sub-paragraphs the principal agent problems applying to this research are discussed.

Principal agent theory can also be used to describe the relations between client – principal – and contractor – agent. This relation is an extreme version of the relation described above; the contractor holds all steering power at the execution of a project while the client's company objective is normally different from the contractors' interest.

This research is written from the contractors' perspective and assumes that he has no other than the client's interest at heart during project operation. Therefore the contractor-client relation will receive inferior attention in this research.

3.3.1.1 Asymmetry in information

The hidden knowledge and information issue becomes clear from studying the different levels of information access surrounding a project. Within a company it is evident that the amount of information available differs between the organisation layers. The agent (the vessel staff) has a strong influence on the decision making since the agent has access to information the principal (head office) cannot gather without the agent's cooperation. The agent may write down that action was taken in daily reports but in reality business continues as usual. The principal can sent representatives to the vessel regularly, but it is never possible to monitor every action on board. This is a common reality in environmental matters for many companies in the shipping industry; principals simply have no proof available. Head offices are searching for control mechanisms such as black boxes on board that register actions.[a]

To prevent a conflict of interest between principal and agent the goal of the company needs to be clear to all parties. If there is no insight or solid proof on the ship of how reducing emission will actually improve the company result and / or the agent's individual remuneration the agent will not be motivated to change actions.

3.3.1.2 Hidden interests

It is possible that the agent has personal interests that are different from the principal's interests; these personal interests are usually unknown to the principal. A hidden interest can be the financial interest of the agent. The agent will choose her actions in such a way to maximize her

[a] The statements in this paragraph are based on information gathered by listening to discussions between Officers – when confronted with environmental issues – of different companies, in interviews and in private conversations.

expected income. Protecting the company's reputation can be of a lesser interest to the agent since he or she is less interested in the companies' long term success.

However, there is more than just the financial interest which can be of importance to the agent. The agent is equally interested in maximizing her work pleasure. For vessel staff freedom of choice is an important issue. The idea of leaving control over speed and acceleration up to a computer or pre-defined schedule is not too appealing to Officers; it will give them an idea of having less influence on their work.

On the other hand the influence of vessel staff can also become larger by providing them with larger control over operations management. The optimal balance can be identified differently at each moment on the ship and requires different types of decision making by vessel staff. The handing over of more responsibilities to the ship gives the staff more influence on the systems' performances. At the same time, it decreases the influence the head office has on the vessel staff. The steering of agent behaviour will become even more difficult for the principal.

3.3.1.3 Hidden action

How to enforce measures on board is an important issue when deciding to provide vessel staff with extra responsibilities over operations management. It is difficult to control what happens on the ship. Correct filled out documents are no guarantee for correct actions. The following example of ballast water changes shows where this can lead to in shipping.

Species that cross the ocean in the ballast tanks of vessels can multiply exponentially inside the tanks and often do not have natural competitors outside their natural habitat. This causes misbalances in the flora and fauna which can have terrible consequences for other species and the environment. To prevent these changes vessels that cross the ocean are supposed to change their ballast water at open sea during their voyage [[49]].

In reality changing ballast water at open sea causes delays and possibly, when weather circumstances are bad, dangerous situations that require much attention from the staff. For these reasons it happens regularly that Officers choose not to make the actual change. However, as long as paperwork said the change was conducted, it is impossible for head quarters or authorities to control this.

Without black box information it is difficult to control the carrying out of emission abatement measures. The agent can easily claim to implement slower sailing or acceleration but the principal will not have constant insight into exact actions.

3.3.2 Responsibility on board / work load

If an emission optimization model or other measures are introduced on board, this needs to be planned carefully. The idea of giving the vessel staff the responsibility of calculating the optimal balance in operations management may not be welcomed by the staff that has no desire to take care of such 'administrative' tasks. Before doing research or implementing new measures it is important to determine the willingness of the people on board. The right officer(s) need to be selected for the management of the model on board to reduce the risk of resistance from the staff as much as possible. The man hours invested need to be awarded so extra time needs to be available in the work schedule.

When discussing environmental measures doing paperwork seems to be an important issue for vessel staff. Many Officers consider their workload as heavy and identify a continuous trend towards having fewer and more non-English speaking staff on board. According to some, this is an extra burden on the workload of Officers. Another issue in this is amount of paperwork there is to be done on board; in particular the amount relating to environmental regulation.

A solution to this can be to place an administrative officer on board, currently either the 1st mate is assigned as the environmental officer or the captain takes care of all administration. An institution like the Green Award (paragraph 0) credits the ship with extra points if an extra administrative officer is onboard. Having an administrative officer relieves part of the workload and therefore, increases the social acceptability on board the vessel as the other Officers will object less to the system if there are no extra actions required of them. This will be an important criterion for the success of sustainable developments.

3.4 Relation contractor versus subcontractors

Dredging contracts are often fulfilled with the assistance of sub contractors. The world's dredging fleet is limited, especially for larger vessels. Being employed with a few vessels as a subcontractor on projects provides the contractor with security of income.

If a subcontractor is involved the principal agent problems become even more severe since the vessel staff of a subcontractor does not strive towards the same company objectives as the contractor. Figure 3-3 shows that in this situation there is no individual project office for the sub contractor – vessel staff reports to the project office of the main contractor, but also to their own head office. This can lead to a conflict of interest if vessel staff is not properly incentivized to strive towards the project goals.

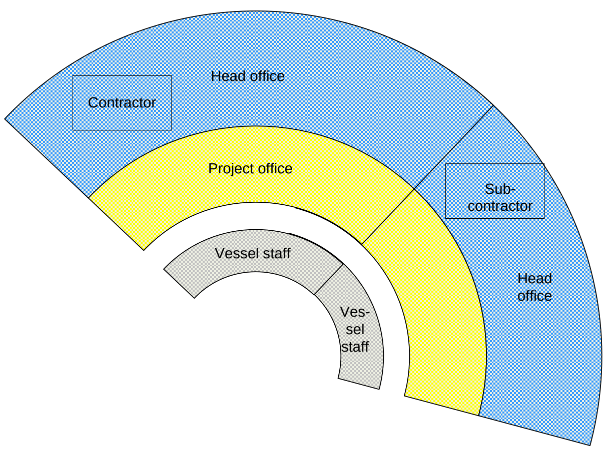


Figure 3-3 Relation between contractor and subcontractor (part of stakeholder analysis)

3.5 Contract design

For the main contractor of a project a reduction of emission is beneficial for both financial issues and improvement of reputation. A subcontractor can profit of a reduction in fuel and emission costs, but most likely not from the improvement in reputation [[50]].

An internet poll [[51]] stated that one third of voters believe that fuel prices can be transferred to the customer and higher fuel prices will not lead to lower consumption. The dredging industry usually works with long term contracts. Prices are extremely competitive and contracts can be fixed which makes it interesting to investigate if it is indeed more lucrative to the contractor to always increase speed. The structure of the project's contract should be considered thoroughly when providing recommendations to contractors for abatement of emission.

3.6 Flexibility of measures

An important issue, when designing measures – a decision making tool – for operational improvement, is the intended user of the tool. Justification for this is found in human factor engineering (or ergonomics) [52] where the tool needs to be designed for the user instead of the other way around.

The initial users of the model will most likely be at the tender of a project, the department that calculates the work and provides the client with different options for the work execution. The calculation of the work is done based on this department's decisions. On the other hand the staff on the ship should also be able to see what the results of their actions are. They have best insight into which options are easiest to realize, but cannot always oversee what would be the consequence for the overall performance of the project. An overview of what the effects of such changes are on the performance indicators can be helpful to vessel staff.

To facilitate adjustment to the different layers of potential users – operational, tactical and strategic – it is important that a flexible model is designed. Not all factors within a model are useful on all levels. Certain factors can be of interest during vessel operation, while the consequential time loss is irrelevant during the tender phase. The model needs to be able to deal with these differences and be applicable in different situations. Also the work situation and knowledge of the different users is considerably different and therefore asks for different interfaces.

3.7 Relation dredging contractor versus outside world

Next to the process relations within the company the stakeholder analysis shows multiple external actors which are referred to as the outside world. The relation between the dredging contractor and the outside world is important to assure successful process change. An important rationale for a dredging contractor to put effort in emission reduction is its objective to improve its reputation (Figure 1-1). A company's reputation can only be improved if the realized process change is visible to the outside world. This requires solid communication about measures and on board operation but also appropriate contract design.

3.7.1 Image of dredging

Not only is the improvement of their own image of importance to a dredging company. The image of the entire industry is almost of equal importance, specifically so, because of the small number of players, which makes the distinction between company and sector much smaller than in other industries.

Currently, the image of dredging is often for it to be an environment destroying industry, even though great efforts have already been made to reduce the impact on the environment.
An example of this sometimes distorted image of dredging can be found in the environmental actions held against the Boskalis vessel 'Queen of the Netherlands' at her arrival in Melbourne, Australia. Every effort had been invested to assure compliance with the strict Australian environmental regulation. Trials had been performed to measure sound pollution to fish, but

public opinion can easily be steered by a few fanatics that mark the vessel a bay destroyer [[53]] [[54]] [[55]].

To assure that the society adopts a correct view of dredging it is important to communicate well with both governments and citizens. Sea vessels can be seen as plants that operate far away and interact little with land based activities. Dredging vessels on the contrary spent most of their operation time close to shore; this makes social acceptability even more important.

During the course Maritime Environmental Awareness[b] a discussion was held on the image of shipping and how this is influenced by shipping itself. There is a lot of controversy on this subject. Some of the (future) Officers indeed want to be proud of their profession and acknowledge that the way they handle the environment plays a crucial role in that. On the other hand there is also a movement that claims not to care about public opinion on their work. They feel like it is also part of the myth of shipping not to speak about what exactly happens in their business and the relative freedom on board is part of why they choose for this profession.

The opinions on how the fact, that sailors have large environmental awareness, should be made public are twofold. Some acknowledge the need of communicating their level of awareness themselves to the outside world. Others feel that the outside world should in particular reach out to them and acknowledge the fact that they are sustainable. This can be one of the strong issues that come up when confronting employees (of different companies in shipping) with environmental issues. Vessel staff can often seem somewhat negative and can constantly be critical about the actions of other people, vessels or enterprises.

3.8 Realization of change: hierarchy and conservativeness

As described above hierarchy and the conservative character of the dredging (or shipping) industry make the realization of change difficult. Young Officers – within their education – are already sceptical about possibilities for change; possibilities to have an impact on superiors are not expected to be plentiful.

The victim role ('slachtofferrol') is easily adopted, combined with a fatalistic role of not being able to influence actions. The issue of hierarchy on ships is very important for this matter. The general belief is that hierarchy is important to enable quick and adequate decision making; especially in distress. On the other hand there is acknowledgement of the fact that hierarchy sometimes stands in the way of change and especially of change initialized by young people.

To have effective realization of change it is important to deal with the issues of hierarchy and conservativeness. Emission reduction means a radical breakthrough in routine and familiar relations. Reduction measures and systems should be designed to deal with these issues and contain mechanisms to change routine.

3.9 Conclusions process perspective

Changing operational behaviour on all levels of a dredging contractor organisation requires a solid process design. Introduction without profound consideration of the process can ignite resistance within the company and from external stakeholders. The problems addressed in this chapter ask for a specific type of solutions. Part III of this research will discuss the field study for

[b] Maritime Awareness Course facilitated by ProSEA in September 2007 (www.prosea.info)

emission reduction by operations improvement carried out with the dredging contractor Boskalis. After the discussion of this field study a framework with possible solutions will be proposed which can facilitate the process change; in chapter 11 a synthesis with specific recommendations for this process with a dredging contractor will be proposed.

4 Institutional perspective

The institutional perspective describes the network of institutions affecting emission of dredging vessels. It is important to consider the institutional environment surrounding the problem to make sure designed solutions are legally possible but also that they are recognized as effective solutions within the institutions.

Institutions are defined as "ways of organizing activities [[56]]." Institutions are social structures or mechanisms that govern the behaviour of two or more individuals.

To get a perspective of the institutional issues the dredging industry has to deal with concerning emission, an overview of the institutional background is sketched in this chapter. First the different levels of institutions are described:

- international
- national and local
- market-based

For each level an example is given. Secondly the effect of the difference in priorities of emission with different authorities is described. Finally the interaction of the institutional background with the proposed abatement methods of this research is treated.

4.1 International authorities

Different types of legislation and regulation apply to this issue as there are different authorities involved. The most important is the International Maritime Organisation (IMO) which is part of the United Nations. Their mission is: 'Safe, secure and efficient shipping, on clean oceans' [[57]]. Until this day almost all regulation in shipping is based on their institutions. Additionally there are some rules and guidelines from national governments or the European Union. However these are difficult to enforce since shipping mostly takes place on international territory.

Annex VI of the International convention for the prevention of the pollution of ships (MARPOL) [[57]] provides worldwide regulations for SO_x and NO_x emission from ships. For CO_2 or other Green house gases MARPOL merely provides guidelines. An update and expansion on Annex VI is due to be proposed in 2008; but as with all international legislation it takes a long time to be developed. At this moment practically all organisations, whether public or private, are waiting on what institutions the IMO will design before taking further actions. Therefore pressure on IMO to take the lead is growing while, simultaneously, expectations are limited. The enforcement of international regulation is always a difficult issue.

Next to this the European Commission provides legislation for air pollution. The European Commission is responsible for almost all legislation on pollution; in comparison with the IMO the EU does have possibilities of enforcement, like fines and withdrawal of subsidies. Since the EU is a supranational organisation it is able to enforce laws on all seas that lie within its borders. When ships go outside the territorial waters of the EU the Commission is powerless and has to rely on the IMO. Basis for the policies of the European Commission is its Strategy on the prevention of air pollution [[58]]. Like MARPOL Annex VI this strategy could use updating with respect to international developments. The EU has put pressure on the IMO by indicating that they absolutely must come up with new measure this year or else the EU has to take the lead. An important issue to consider when regarding the EU is that, generally speaking, setting too high standards for ship pollution will damage the economic position of member states.

4.1.1 Sulphur Emission Control Area's (SECA)

An example of an institution on air pollution of ships from an international authority is the legislation on sulphur content of fuel at the North and Baltic Seas. Ships in that area need to use Low Sulphur Fuel Oil (LSFO) for their engines; LSFO is fuel with a sulphur content below 1.5 percent by mass (% m/m). IMO MARPOL Annex IV [[49]] allows 4.5 (% m/m) while the industry averages lay around 3.5 (% m/m). SECA law is applicable in specific areas where SO_x concentrations are high and potentially harmful; at open sea far from shore Sulphur pollution will just rain down in the sea without causing any damage. The European Union has decided that the North Sea is considered a SECA as from the 11th of August 2007. The International Maritime Organisation (IMO) requires the same as of November 2007. This deviation is a good example of the lack of coordination between EU and IMO. At the Baltic Sea the measure has been valid since May 19 2005 [[59]].

Opponents of SECA-regulation state that when the life cycle of the fuel is considered the desulphurization-process of fuel into LSFO takes a large amount of energy and therefore produces additional CO_2.

SECA regulation makes it necessary that a ship, which enters the North Sea area coming from a remote location where no LSFO is available, to make a stop at the outside of the SECA to bunker LSFO. Such a stop harbour could for instance lie in the West of France. The consequences of such a stop are uncertain; especially the extra time and fuel it will cost to make such a stop might not be worth the gains in Sulphur emission. This situation might apply more regularly to a dredging company than another shipping company. A large container ship sails around the world when only having bunkered in its home port. They can easily calculate the amount of LSFO they will need to sail out of the SECA and back into it again when returning. Since dredging activities are usually on a somewhat fixed location for a longer period of time a dredging ship will not be able to have a stock of LSFO available all the time. Additionally such regulations will affect a dredging company more if their work is situated in a SECA; the ship will then need to run on LSFO continuously.

4.2 National and local authorities

Vessels have to comply with all legislation enforced by the country under which flag it sails; issues like safety and equipment standards are specific for each country. These differences can be substantial; as are the differences in taxes and additional costs. A company is free to transfer its vessels to a different nationality if legislation or taxes there are more convenient. A flag state is not likely to design strict legislation on operational performances of the ship such as air emission. This will limit its attractiveness as a flag state and limit tax incomes, while the air pollution scarcely affects the countries territory; only when the vessel is actually sailing in its waters.

On inter-territorial waters the limited amount of IMO-regulation applies so most vessels spent the largest part of the operations practically free of institutions. Dredging holds a special position in shipping since long periods of work take place in coastal areas where the land is owned (usually by national governments) that do have enforcement power. Therefore national institutions affect dredging companies before they affect other shipping businesses and it is wise for the dredging industry to look beyond the regulations of the IMO.

Next to national governments there are local authorities that play a role in the prevention of emission, such as port authorities that can create rules about the type of ships that are allowed into their waters and the behaviour these ships are supposed to show. Port authorities are able to enforce these rules through harbour fees or in severe cases even through harbour police. Regulations from port authorities may seem to have less effect on the dredging industry as dredging vessels spent little time in ports compared to other industries; however many of the projects of the industry take place in or near ports when port authority legislation is applicable.

Local authorities do not only provide legislation on emission but are sometimes equally involved in the design of market-based incentives for emission abatement such as treated in paragraph 4.3.

4.2.1 Shore power

There are not yet numerous examples of national or local institutions and the institutions that do exist are usually quite straight forward. An example can be that ships are obliged by port authority to use shore power during harbour docking. This has a positive effect on NO_x and SO_x emission since shore power has been generated in a relatively clean way on shore. The effect of shore power is not necessarily positive on the balance of production of CO_2 dependent on the fuel used and efficiency losses for the electricity generation on shore. In the city port of Rotterdam there are recently established facilities for shore power for inland vessels. A research of possibilities of shore power facilities establishment on the industrial area 'Maasvlakte' did not result in positive expectations of feasibility [[60]].

4.3 Market based institutions

Next to legislation and regulation there are also market based institutions aimed at the reduction of emission. Market based institutions try to motivate industry to limit their reductions by providing financial incentives. They can be created by any type of organisation, but usually the start is facilitated with public funds; if designed correctly subsidy by public authority will not even be necessary.

4.3.1 Green award

An example of a local market based institution, partially aimed at the reduction of emission from sea vessels is the green award [[61]]. This is an organisation that provides a certificate which will give the holder rights on a reduction on port fees in member ports everywhere in the world. This is an international program but effects are local. The organisation was started in cooperation with Rotterdam Port authority but is now financially independent. Certified vessels pay a certification fee with which the foundation covers its expenses. Ports offer reductions on port fees with the incentive of hosting more clean vessels in their waters.

Customers are attracted to the green award based on two premiums: I) image incentives and II) financial incentives. Financial incentivized clients decide on participation in the green award program because they often visit a port that offers green award reductions and believe their investment will reduce their costs. At this moment green award only applies to tankers and bulk carriers, but there is a window of opportunity for other vessels to get involved in the future, so dredging companies could lobby for themselves to create an advantage.

4.3.2 Emission rights trading

Because the subjects of emission and emission rights trading are gaining attention in the world of shipping and the media, the two are often matched in media and public discussion, so many ask if an emission rights trading scheme is not the solution for the industry.

An emission rights trading scheme is an example of a large scale market based institution. The concept of emission rights trading is based on a certain amount of allowed emission. A producer of emission will have to buy rights to do so if he produces more emission than he is allowed to do. In order to keep business running, he will have to acquire more rights on the market. On the other side of the market a rights owner, that emits less than he is allowed to, can put his rights up for sale, turning them into profit.

The Kyoto protocol foresees in possibilities for emission rights trading for green house gases and acknowledges the Clean Development Mechanism which allows rights seekers to realize reductions in developing nations to compensate for their own. The objective of the emission rights market it that reduction is realized at the most economically feasible location, independent of its location.

For an emission rights program it is important to identify the difference between Green House Gases and other emission. As was explained in Chapter 2 Technical Background the emission of Green House Gases have effect on a global scale opposed to emission that cause health effects or acidification that only causes problems within a limited range from the source. For the second type of emission a trading scheme is feasible if concentrated on local scale trading, keeping the pollution in one area. In the Netherlands there is an example of a NO_x trading scheme but for land based sources. This program is not a cap & trade program, where there is an absolute ceiling to the amount of emission in an area, but a 'Performance Standard Rate' (PSR). PSR means that the amount of emission a facility is allowed to emit is relative to its production. The PSR is determined every calendar year by the Netherlands Emission Authority [62]. An example of a cap & trade scheme for SO_2 can be found in the United States of America for power facilities [63].

At this moment there is no equivalent emission rights trading scheme applicable on shipping as there are on land. The European Commission sometimes does mention plans to include shipping into their emission rights trading program but this is a delicate issue. If the EU would enforce this unilaterally without involving other areas of the world, the competitive position of ports and companies in the EU would be considerably affected. For instance the Port of Rotterdam – which is now one of the cheapest Bunker ports in the world – would become less attractive as a result of the cost of spending (extra) bunker time in the Rotterdam port and paying for emission during that time.

Recently Euro Commissioner Borg of Maritime Affairs claimed that shipping cannot be included in the emission rights trading scheme as it currently exists, because this would hurt the position of the European industry too much. Borg claimed that global possibilities needed to be investigated first, which puts extra weight on the developments at the IMO [64]. Postponement of the extension of the trading schemes to sea shipping does not guarantee that dredging will not be affected. Dredging holds a unique position within the shipping industry. The dredging sector could just as well be included in the land rules; the work of a dredging contractor will then be considered a land based industry. Furthermore, for this research it is crucial which organisation will be charged with the emission rights obligation: the dredging contractor or the client?

4.4 Model institutional environment

Figure 4-1 provides a schematic overview of the institutional environment. The arrow on the right represents the level of hierarchy between the different authorities; the arrow below represents the geographical location where the institutions can be enforced.

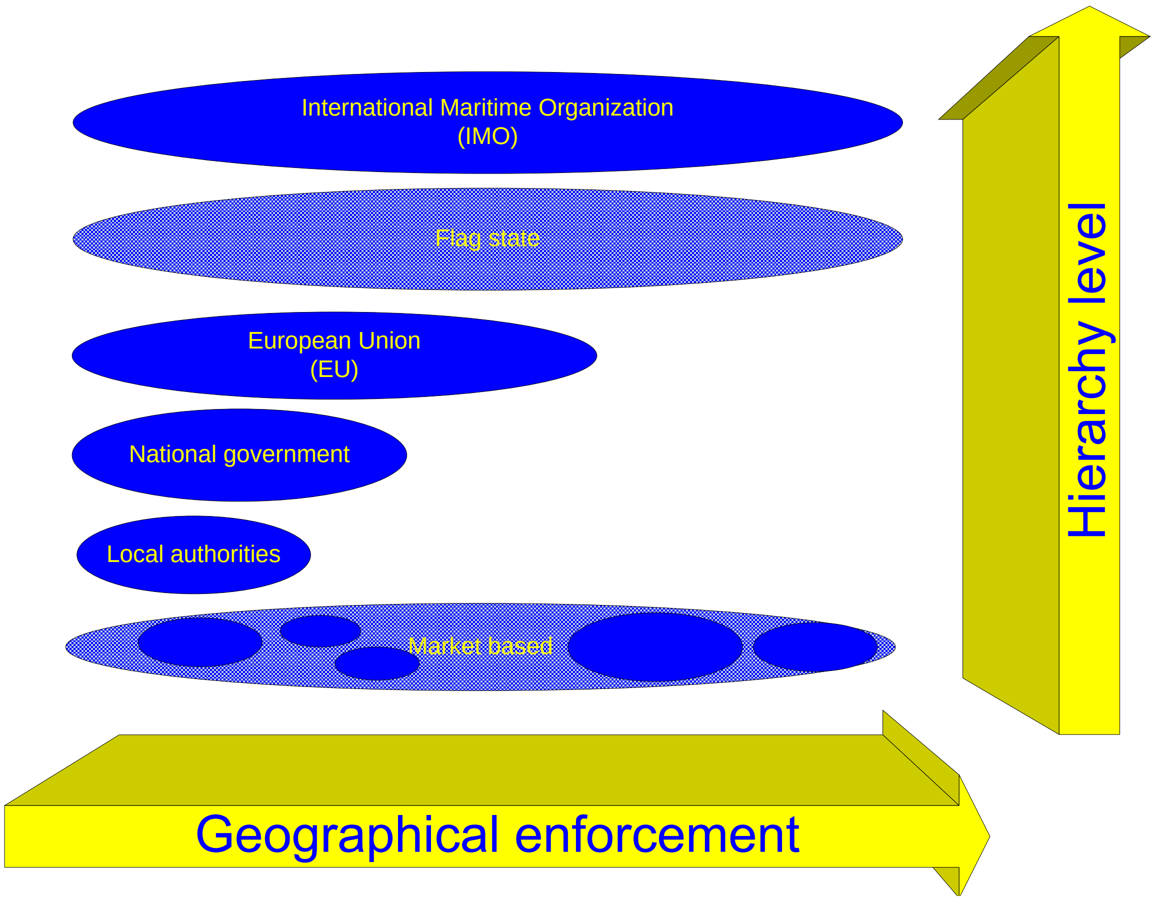


Figure 4-1 Model of the institutional environment

4.5 Difference in priorities

In different parts of the world as well as on different institutional levels the trade-off for which emission is considered most important (in the institutional environment) can deviate greatly. This trade-off is different for each project and for each location. Currently a ship only needs to comply with IMO-regulation, legislation of the country under which flag it sails and possibly some local regulations in coastal areas or ports. This coastal regulation is highly likely to expand. A dredging company holds a special position compared to other maritime industries since dredging vessels spent relatively little time in ports; but much time in coastal areas during dredging activities.

4.5.1 Priorities of Rotterdam Port Authority

An example of how certain areas have different priorities is the region of the port of Rotterdam. Rotterdam Port Authority claims the abatement of NO_x and Volatile Organic Compound (VOC) as their top priority; this is mainly due to strict regulation that does exist for these emissions. CO_2 is named on the priority list right after that – abatement is organized through the Rotterdam Climate Initiative [65]. SO_x has a lower priority since its consequences are not as urgent in Rotterdam [66]. As stated above these priorities depend highly on location; a developing country situated well above sea level is likely to be little concerned by climate change than a well established port like Rotterdam which is situated in a very densely populated location. Both locations will attach considerably different priorities to CO_2 emission.

4.6 Integration of research results with international standards

There are different units available to express emission; the institutional environment has a considerable influence on the type of unit generally used. The unit most commonly used is [g/kWh]; this is the proposed unit for further IMO regulations [67]. When steering on [g/kWh] only the engine builder and fuel produce are involved, legislation that will use this unit stops at the output of the engine; without consideration to how efficiently the produced power is transformed in to usable production. Measures that go further and are aimed at improving the performance of the complete operation process are mostly left out of consideration by institution designers.

To bridge this gap, emission is expressed in this research in units that consider the complete dredging process – 'Performance Standard Rate' (PSR). For a cargo vessel a proposed unit is [g/mile]. This research proposes that for the dredging cycle mass emission (m) per volume of dredged material (V) in [g/m^3] are used. The unit that needs to be minimized in this notation is the amount of [kWh] needed to produce one cubic meter of dredged material.

There is a strong point of attention when using self-designed units, since it is unlikely that these units will be taken into consideration by legislators in the near future. Although differing from standards poses a threat to the usability of this research not proving the inaccuracy of current standards would not do the industry any good either. By this research the superiority of proposed measurements will be made clear. Next to this, the wish is ventilated that industry takes the proposed measurements into account and assesses whether discussed standards should be changed in the future. For the recognition of efforts in improving PSR it is important to start lobbying with authorities and to convince customers that this emission indicator gives a more complete view of the emission performances than the unit [g/kWh].

4.7 Conclusions institutional perspective

Institutions to abate emission from shipping are not yet numerous. The global character of the industry causes difficulties of hierarchical and geographical enforcement power which need to be resolved before institutions can be truly effective.

Most authorities seem convinced that an emission right trading scheme as on land is not yet feasible at sea, which seems to give the industry some freedom for self-initiative. Simultaneously, the dredging industry should stay alert, since it is not unforeseeable that project work will be considered a land source. In that case contractors or clients could be facing emission rights requirements in the near future.

The examples in this chapter and in literature show that institutions aimed at ship emission currently have a rather technical character – there is not much recognition of operational efforts

– which is not expected to change significantly at short term. Institution designers, currently focus exclusively on tangible artefacts. The latest revision of MARPOL Annex VI that discusses the options in consideration for new regulation, exclusively considers technical measures [[57]].

At this time, very little and only local examples can be found where changes in operations management that cause reductions in fuel consumption are officially recognized by institutions as abatement method. However, if emission from ships will be monitored continuously this will certainly have an effect. Acknowledgment of this type of measures on institutional issues will require effective lobbying by the industry as well as sound proof of achieved effects.

Part III Field study

5 Royal Boskalis Westminster nv

This chapter provides information about the field study that was done at Royal Boskalis Westminster nv. Firstly, the rationale for this research and the phases it aims to facilitate are described. Secondly, the way Boskalis is organized is described. Finally, the management of information that is important to this research is elaborated upon.

5.1 Rationale

To answer the research questions a study has been conducted at Royal Boskalis Westminster NV. Boskalis is one of the largest dredging companies in the world and aims to be forerunner in both dredging technique and environmental awareness. To enforce this position Boskalis has set itself the goal of reducing their fleet's emission within the next few years; anticipating on increasing international public and governmental attention and policy measures on this subject.

The study focuses on one of Boskalis' largest dredging vessels, the trailing suction hopper dredger: "Queen of the Netherlands." This ship has been chosen as case material because it is not completely new (construction year 1992) but still it is relatively modern. Therefore, it can be seen as a good representation of the present fleet. At this moment a new ship is equipped with the most advanced techniques, but little thought has been given to emission reducing equipment during the construction of older ships like the "Queen of the Netherlands". The expected lifetime of a trailing suction hopper dredger is at least twenty-five years. Since ships like the "Queen of the Netherlands" will not be replaced in the near future it is interesting to find out if it is also possible to reduce emission with non-technological measures such as changes in operations management. This is a cost-effective way of reducing emission and therefore an interesting option to further elaborate upon.

Prior to this research the management of Boskalis presumed that there were in fact emission reductions to be achieved but no exact data was available on feasibility and size of effects. The purpose of this case study was to analyze the ships' operation to provide information that can facilitate the decision making process by Boskalis whether to take actions in this direction. If a decision is made to take actions by changing the ship operation the question remains how to implement such actions within the company.

Figure 5-1 Research phases within Boskalis

The field study conducted with Boskalis consists of three phases (see Figure 5-1): (I) Analysis; a quantitative analysis of the emission of the Queen of the Netherlands, (II) Decision making; an optimization model supporting improvement in operations management and (III) Process change; a framework with recommendations for the process to realize change within the company. These three aspects can be translated to general situations, applicable to other ships or contractors and can serve as guidelines for more sustainable dredging.

5.1.1 Areas of attention

The research approach described in this thesis is specific for the SEPAM education but fairly unknown to the company Boskalis. Not many efforts have been made there to solve problems in such a non-tangible way. Especially in a department as the Central Plant Management, that is responsible for the vessels, the traditional engineering approach is most common. This asks for special attention when explaining the research and gathering support.

An important problem, sometimes mentioned when raising the issue of sustainability within Boskalis, is the integration of the subject in the complete company. There is a large awareness of the need for sustainability, especially on management level. Translating this awareness into concrete measures that can be used on the work floor is more difficult and a step the company finds hard to realize.[68] The idea of changing the operations method of the ship and possibly even taking back speed is often welcomed with the words: "That is impossible; works are calculated up until the very last minute. We cannot differentiate from the schedule." For this reason changes in the operational system will need to be integrated on every single company level starting at the basis of each project: the calculation of the work offer. A project manager can implement the emission reduction measures only if time and money are available to him in his total assignment. A possible solution for this is to offer the client a tender with different tariffs and time schemes: one with special emission measures and one without; additional options could be for less toxic emission (less NO_x and SO_x) or a climate friendlier option (less CO_2 and other GHG). The client will eventually pay for how clean he wants the project to be.

5.2 Description of organisation structure Boskalis

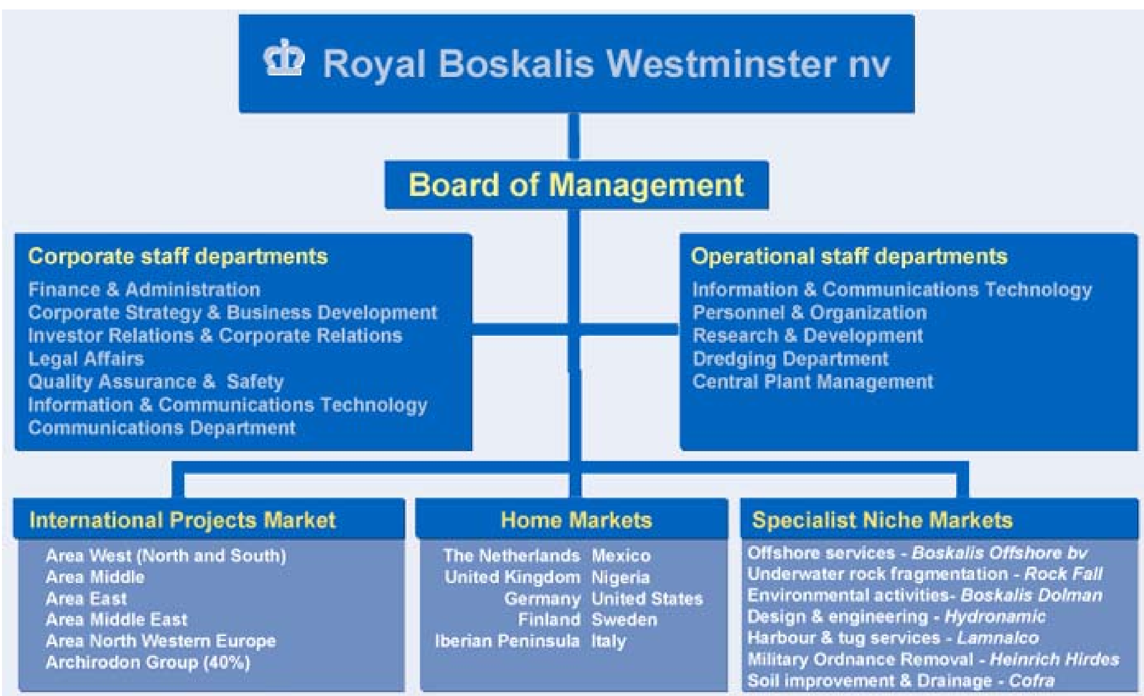


Figure 5-2 Organisation structure Royal Boskalis Westminster nv

The organisation structure of Boskalis shows that the company consists of organisation broad services and is divided into specific markets. Organisation wide services can be called upon from all markets. To gain a better insight into the division of responsibilities within the company the three most important departments for this research are described in this chapter.

5.2.1 Central plant management

Central Plant Management (CTD, abbreviation based on Dutch name) acts as the "owner" of the vessels (plants) of Boskalis. CTD is responsible for new build, maintenance, staffing and all other issues directly related to the individual vessels. Area- or project-management can request vessels to be assigned to their work for a certain period.

5.2.2 Area markets

The international project market consists of several areas that are responsible for the acquisition and execution of projects in their assigned geographical location. They request dredging vessels and other equipment to be assigned to their projects and are responsible for planning of the ships operations during the time the ship is at work in their area.

5.2.3 Dredging department

The dredging department is responsible for the calculation and planning of Works. The responsibilities of the department are twofold; on the one hand it calculates the project before a tender is made, so it estimates the costs and time it will take to complete a project. On the other hand, it is responsible for the calculation of the best possible work method on projects after a project has been acquired. When planning is made before a tender has been acquired the project is estimated based on a particular type of ship. When the work is acquired the type of ship from the tender usually is not the actual ship and thus recalculations need to be made. The dredging department is responsible for the high level calculations of the project as a whole. Naturally more specific calculations need to be done constantly on all levels e.g. the project site but also the vessel.

5.2.4 Vessel management

On board the vessel the Captain, together with his Chief Engineer, is directly responsible for all operations. The project management assigns the Captain what activities the vessel has to perform, on which location and in which way; the vessel management plans and organizes the precise carry out of this on board. They keep in touch with the plant management to organize all maintenance and supply matters such as dry docking and bunkering. On board the Chief Engineer is responsible for the engine room while the Captain is end responsible for what happens on the bridge.

5.3 Knowledge management

The calculations made by the dredging department for the design and operations of projects need to be based on theoretical figures as well as data from experience.

Boskalis keeps most of this information stored in an Oracle-database which can be in contact with spreadsheet models in Microsoft Excel. It is possible to choose a certain vessel and material to be dredged in the database and Excel will provide numbers for values like required power to replace the dredged material. This database holds basic information about specific fuel consumption of vessels in all different stadiums of the dredging cycle. However, for the "Queen" this information is purely based on experiences on a related vessel and rough calculations where the numbers of the weekly consumption are simply divided by the time the different phases were conducted within one week. The fuel consumption sheet has indicated on the sheet "that these numbers could use validation on board." The dredging department has indicated to be interested in new numbers about the actual fuel consumption of the Queen for future calculations of projects planning.

A few years ago calculations were done at the dredging department to see how much influence the consumption of fuel had on the price of work and whether it could be more attractive to reduce vessel speed. This measure would result in sacrificing a small part of production which would in turn be compensated by lower fuel costs. At that time the calculations showed that this effect was too small to be feasible; the production should always be maximized regardless of the level of fuel consumption. These calculations were done, however, at a time when fuel prices were much lower compared to present prices and when the emission aspect was not taken in consideration [69].

6 Definition of tests

In this chapter the definition phase of the tests is discussed. There are two reasons for executing tests: The first reason is to provide reference for the amount of emission the vessel produces during the different phases of the dredging cycle. The second reason is to identify whether there are possibilities for operational improvement. In this chapter the methods for testing are described. Secondly, the choices for test location and time are discussed. Thirdly, the details of the project location are given. Finally, the measured variables are described and validated.

6.1 Type of tests

This paragraph describes the different types of test that were designed: reference measurements to investigate the current situations; and experiments to analyze the influence of changing steering variables.

6.1.1 Reference measurements

To be able to compare the performances of the system and optimize the operations management it is essential to have information on the current situation as this will serve as reference. The complete life cycle of the dredging process needs to be analyzed to provide values for the different performance indicators during normal operation.

At this time Boskalis has no clear data available for the fuel consumption of the different phases of the dredging process; the reference measurements are designed to provide these. Apart from being used as a reference for further experiments in this research, they can by be used as calculations and estimations of future works by the dredging department. To provide material to compare and validate measurements it was desired to measure the fuel level continuously - using the fuel meter - as well as the fuel flow - using the fuel rack. Since the fuel level meter turned out not to be available on board, this method could not be used.

6.1.2 Experiments

After the execution of the reference measurements the influence of changes in operations management was to be determined. The objective of the experiments is to identify relations between operational action and fuel consumption. For this purpose experiments were performed with manual variation of steering factors. The identified relations can later on be used to investigate under what circumstances the operations of a dredging contractor can be improved.

6.2 Test method

In this paragraph the method of testing is discussed. The time scale for testing, the choice of test location, the equipment used, as well as the cooperation with vessel staff are described.

6.2.1 Choice of time scale

The fuel consumption of ships at Boskalis including the "'Queen of the Netherlands'" is normally measured on a weekly basis only. Prior to this research there was no indication of what the effects of changes in operational functions were on the specific fuel consumption per vessel. A few ships are equipped with fuel meters which can actually measure the flow of fuel going into the engine but the accurateness of these measurements is low.

Assumptions of the influence of operational functions on the fuel consumption could be made based on the available data about weekly fuel consumption. The scientific value of conclusions based on weekly measurements is questionable, because there is little information about the relations between fuel consumption and operational changes. During one week environmental factors can change substantially and this could be a dominant factor for changes in fuel consumption; more important than a change in operations management. Dredging projects usually require many repetitions of one cycle but no two cycles are completely identical due to occurring unforeseen events.

Another disadvantage is that experiments would be much more expensive with weekly measurements only, since it is more difficult to change events for a complete week compared to for a few minutes or seconds. The possibility of a getting good cooperation with the staff is equally higher with shorter experiments as this will ask less of their time and efforts. Especially for initial experiments where the goal is to get a first insight into possibilities for reductions it is desirable to do many short tests. Later on, tests could also be run on a longer time scale or at different ships. By starting with shorter experiments the impact of changes on the long run can be determined beforehand. In this research the fuel consumption needs to be measured continuously and tests performed on short time scale.

6.2.2 Overview measurement scheme

To be able to fill in the complete objective function first we need to provide an overview of the different amounts of emission produced. The way these have been calculated will be explained in this section.

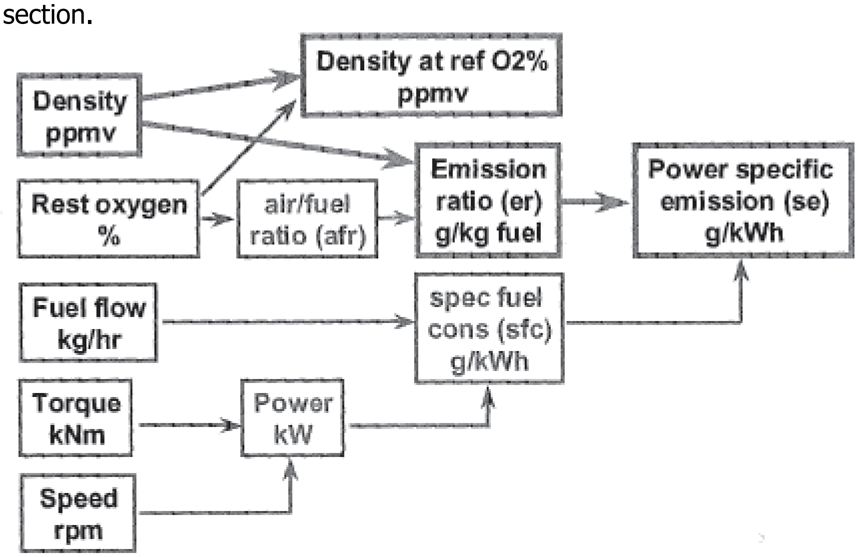


Figure 6-1 Basic scheme of sensors and data processing for emission measurement [70]

The figure above provides a schematic overview of sensors and data processing needed to determine the production of emission on board a vessel according to [70].

On board the 'Queen of the Netherlands' power is calculated automatically from torque and engine speed (constant at 500 rpm). Fuel flow is not available directly so in this research fuel inlet or power data are used to calculate this.

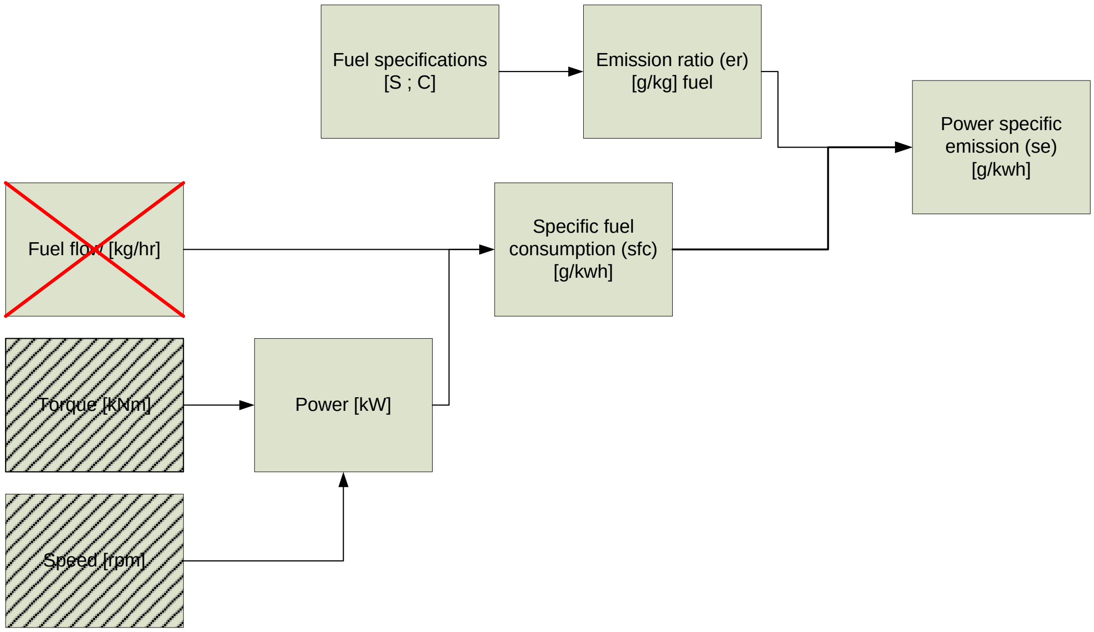


Figure 6-2Alternative measurement scheme used in this research

The scheme of this research zooms in on the category fuel consumption. The fuel flow was not available, therefore this category was replaced by power measurements and specific fuel consumption determined by the manufacturer. The emission ratio for NO_x has been equally determined during engine shop trials so this can be used directly for calculation.

6.2.3 Choice of test location

The numbers in paragraph 2.7.1 showed that sailing is the most intensive phase in terms of energy consumption. The fuel consumed by an engine increases exponentially at higher vessel speed because of the propeller law so there is an optimum between income and fuel costs to be identified. Therefore, the first set of tests has been targeted at the sailing phases of the dredging cycle.

In coordination with the plant and area management the best possible timing and location for the experiments was identified. These choices were based not only on where most reliable and interesting data could be gathered but also on where tests would least interfere with the operation of the ship.

A pre-defined minimum sailing distance is required to perform tests; the ship needs to be able to reach maximum speed and hold that for some time. Sailing distances can vary a great deal between projects depending on which sea ground is assigned as a dredging area. When the experiments were first scheduled, in the beginning of November 2007, the ship was scheduled to be at work in Yiti, Oman. On this project the distance between dredging area and connection point is so small that there is almost no time for sailing; after dredging the ship sort of lets itself float freely to the connection point. For this reason the tests were moved up a few weeks and performed at Ras Laffan, Qatar, a project with a sailing time of at least one and a half hours.

Mobilisation (the displacement of a vessel between projects) was identified as a suitable occasion for the performance of tests with 'Vessel Speed Reduction'. During mobilisation there is no project manager, client or manager, so time spent on an experiment will cause fewer objections than it would during project operation. Another advantage of mobilisation is the possibility of performing speed experiments on open water for a longer period with relatively constant circumstances.

The process of acceleration is more difficult to test during mobilisation. A project situation with dredging cycles going on continuously is the best possible situation for this. After the experiments had started, the dates of mobilisation were postponed. This made it no longer possible to perform tests during that phase. Therefore, all experiments had to be held during project operation.

6.2.4 Experiments on board

Within a period of ten days, measurements and experiments have been performed on the ship "Queen of the Netherlands". The values of output-variables were measured using special software for Supervisory Control and Data Acquisition (SCADA). This software measures and calculates a large set of variables, which influence the operation of the vessel, on momentary basis. Special log computer software generates an output of the values (loggings) of variables every 2 or 10 seconds which can be imported into Microsoft Excel and be used for further calculations.

6.2.5 Cooperation with vessel staff

For influencing steering variables during operation the cooperation of the First and Second Officer on duty was required. The experiment schedule was first approved by the Captain and subsequently discussed with the Officers, to decide the appropriate time and location that would assure the least interference between experiment and project planning as well as the most reliable data for the research.

6.3 Ras Laffan project specifications

In this paragraph the project specifications of the test location are discussed.

6.3.1 Time schedule tests

The tests were performed on the vessel "Queen of the Netherlands" when it was working on the construction of break waters for the LNG port in Ras Laffan City (Qatar) from October, 19 – 25, 2007.

Vessel speed experiments were planned during mobilisation from Ras Laffan to Abu Dhabi (United Arab Emirates) which would take approximately twelve hours. This period was perceived as an excellent opportunity to perform experiments with the number and capacity of engines. Acceleration period can be monitored and logged for reference during mobilisation but acceleration experiments are better suited for project situation. When on board of the Queen the decision was made to postpone this mobilisation to a date outside the time limits of this case study.

6.3.2 Ras Laffan port area

The state Qatar is rich in Natural Gas. Ras Laffan Industrial City is designed to become the Liquefied Natural Gas (LNG) hub in the Persian Gulf. There is an existing port which is currently being extended. In Figure 6-3 the port area of Ras Laffan has been photographed from above.

The two piers going into the water are the original breakwaters to protect the port area. The two moat outer lines next to the original piers indicate where the new breakwaters are currently under construction.

Figure 6-3 View from above Ras Laffan Port area

6.3.3 Dredging cycle Ras Laffan

The dredging process consists of different phases that all have different characteristics, load of engines and average fuel consumption. In Figure 2-5 the different phases of the standard dredging cycle were introduced and visualized in a diagram. Measurements and experiments need to be performed separately for all these phases. The exact duration of the cycle is dependent on multiple factors; e.g. the distance between dredging area and discharging area.

In Ras Laffan the dredging cycle has specific characteristics; this can be seen in Figure 6-4. After discharging on one of the two breakwaters under construction (see Figure 6-3), the vessel does not return to the dredging area straight away. It first sails to another area inside the port to remove silt. This silt consists of the remains of the cutter dredgers at work in the port area. The vessel sails loaded with the silt to an area, designated for dumping silt, at open water, not far from the sand dredging area. After a short displacement the dredging can commence again. The completion of one dredging cycle at Ras Laffan takes between 8 to 9 hours; the exact duration depends on multiple circumstances and can therefore differ significantly between different trips.

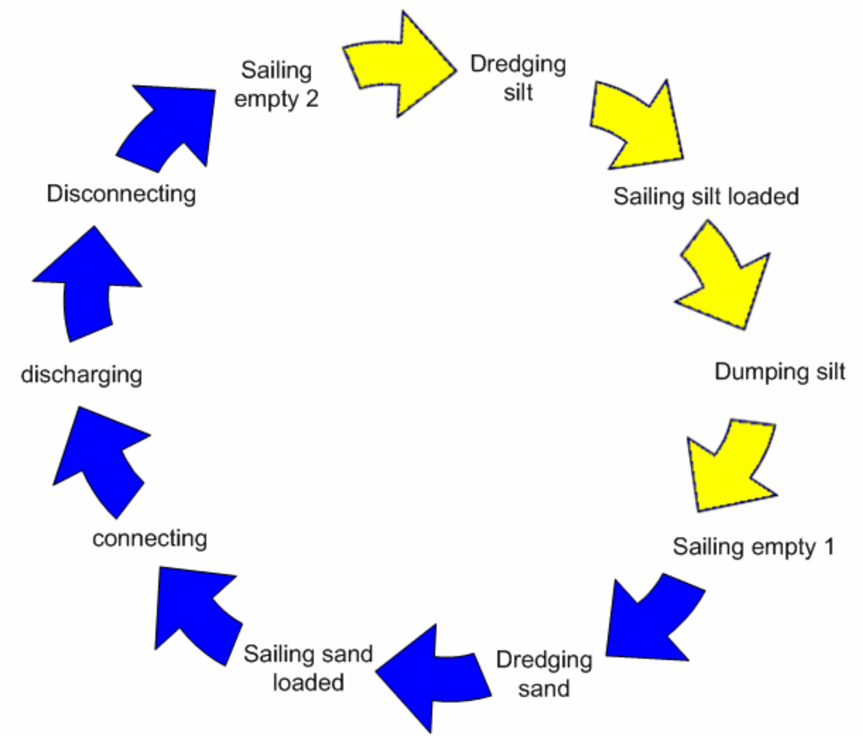


Figure 6-4 Overview of dredging cycle Ras Laffan

6.4 System variables

The experiments of this research relate to the category fuel consumption as shown in the system diagram of paragraph 2.4. In Figure 6-5 this part of the system diagram is shown in an extended version. The green variables are steering variables, purple are environment variables and light blue are the response variables used to calculate the performance indicators.

Compared to the system diagram in paragraph 0 in this diagram only the steering factors that were used during the tests are shown; factors such as vessel trim and dredging pipe angle are left out of the equation. The response variables are shown in more detail in this diagram; e.g. the output power is split in propeller power and generator power. Finally, in Figure 6-5 all environment variables presumed to have an influence on the fuel consumption and that are possible to measure on board - when the SCADA system is functioning correctly - are added. These additional factors are measured for extra information to determine the sensitivity of the results of this research to environmental changes.

Appendix H provides a complete overview of all variables measured on board during the trials.

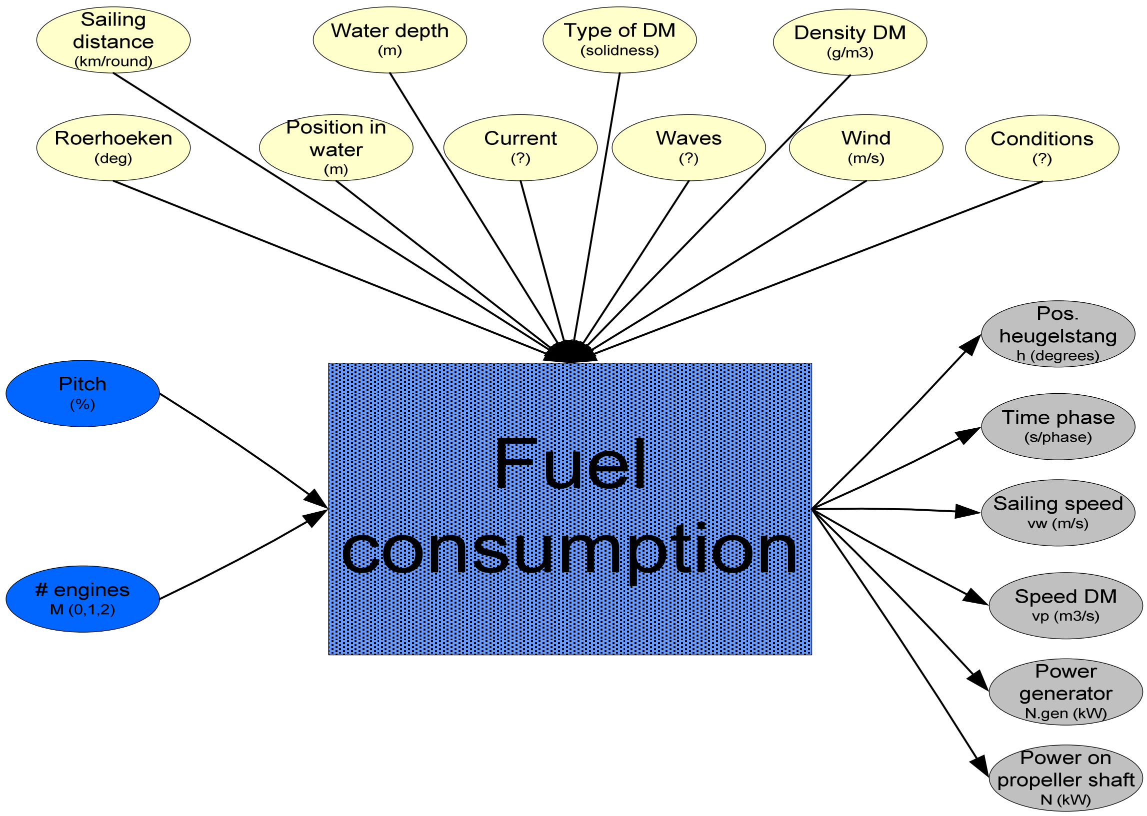


Figure 6-5 System diagram fuel consumption (enlargement of part fuel consumption from system diagram)

6.5 Steering variable Pitch

For the comprehension of the experiments it is essential to have knowledge about the propulsion method of the testing vessel. The propulsion method explains the variable Pitch, the most important steering variable of the experiments. The 'Queen of the Netherlands' has two main engines, which each provide power to one propeller directly. The two propellers combined enable the propulsion of the vessel through water. The main engines also deliver power to two generators that provide electricity to all other equipment on board. The propellers run at a constant velocity of 117 rpm. It is possible to influence the vessel speed by changing the Pitch, the angle of the propeller through the water. At high Pitch the propeller makes a large angle with the flow of the water and encounters great resistance, so the engine needs to provide a large amount of power.

The two auxiliary engines on board are only used during special operation to power the generators; such as port stops, heavy dredging, or emergency operation. They are not considered in this research, because this research focuses on the fuel consumption caused by the propulsion of the vessel.

6.6 Verification and validation of measured values

During verification and validation of the measured variables on board it turned out that a number of variables could not be measured correctly. In this paragraph those variables are discussed.

Also the reasons why they were not correctly measurable and the consequences of this for the research are described.

6.6.1 Unavailable variables

The SCADA log program was started and a list of variables was entered. A few variables were not available in the program. The fuel flow meter did not work at all, so it was not possible to log this for comparison with the fuel rack. These measurements were only desired for comparison means and the accuracy was presumed to be low, so their absence has no direct consequences for the completeness of the measurements.

After the log program was started it was left running for a complete dredging cycle several times. After each cycle the gathered data were analyzed to verify whether the right factors were being measured and to validate if the indicated value was correct. The measured data were compared to expected values of human sense and experience, observations on the bridge and in literature.

Firstly, all variables were excluded that did not provide information at all. These are factors that provide a continuous log value of often zero, which indicates that there is a problem within the SCADA system. If possible other factors were introduced to replace the non-available factors or efforts were made to find the errors in the system. When a factor was not essential to the calculation of the performance indicators – a so called 'nice to have factor' – it was excluded.

6.6.2 Incorrect calculated variables

Secondly, all outcomes were compared with expected values, which sometimes required human observation. When the delivered value was deemed incorrect a replacement was sought to enable calculation of the requested variable. For the 'nice to have' factors no further action was undertaken.

After multiple cycles it was noticed that the logged data of the variable Pitch Star Board (SB) were not matching the data of the meters on the bridge or in the control room. They did match the values on the SCADA control screen, which is also used on the bridge, but they were inconsistent with the values of propeller power and fuel rack. The Pitch is a crucial factor for the results so replacing data were required. It is possible to estimate Pitch from the delivered power and data of Pitch port side. However, Pitch is the most important steering variable of this research and the relation between Pitch and power is being investigated. To be able to give valuable recommendations after the experiments, it is essential to know which Pitch realizes a specific speed.

Researching the values for a direct relation between Pitch SB and Pitch PS did not pay off; no validated direct relation was found. The value of Pitch SB was often around 2/3 of Pitch PS but this was not stable. The way the SCADA system was programmed to read the value seemed to be correct, so the problem was presumed to lie deeper in the system and would require reprogramming the calculation of the value. Since consequences of a mistake in reprogramming calculation would be high, it was impossible for the Electrician on board to make adjustments at that level in the system.

The values of Pitch PS had to be used for the already performed parts of the tests. Pitch is usually varied symmetrically on both propellers and with the values of Propeller Shaft power the star board Pitch can be estimated. Nonetheless as a replacement and extra check the variable 'Pitch lever demand', which logs the requested position of the bars on the bridge, was added for the remains of the test period.

Another observation relating to the Pitch was that both engines were adjusted in different ways. The Star Board engine needs about 5% more Pitch lever demand to reach the same power. Since the bars are usually handled parallel the Port Side engine is providing more power under the current circumstances. This observation does not influence this result directly but it is important to keep under consideration when analyzing data.

6.6.3 Calibration of fuel rack

The position of the plunger of the fuel rack was foreseen to be calibrated during the experiment period. On board it turned out that the position of 100% fuel rack had been calibrated in July 2007. The relationship between minimum and maximum position is linear, so further calibration was not necessary. It is possible to calculate the average maximum position of the cylinders; these values can be used to calculate the fuel consumption.

6.7 From definition to design and execution

In this chapter the test methods, location, and equipment required for the trial period were defined. As well as the circumstances experienced on board and the changes these circumstances caused to the foreseen methods or planning. Consequently, the process of design of experiments could begin; which runs both before and during the trial period on board.

7 Design and execution of experiments

In this chapter the design and execution of the reference measurements and experiments is described. In the paragraphs relating the execution of the experiments, decisions made and problems experienced on board are described. The design of experiments process is cyclical; a preliminary design is made before the trial period. This design is reviewed and adapted to the experiences on board.

The experiments are divided in three categories, which are all discussed in individual paragraphs in this chapter:

1) Experiments sailing speed
2) Experiments acceleration
3) Experiments during phases dredging and discharging

7.1 Experiments sailing speed (A)

Experiment A concerns the reference measurements and experiments with 'Vessel Speed Reduction'. Pitch and the number of working engines are altered to different levels during one sailing phase, which varies the requested power of the vessel and therefore the sailing speed. The purpose of the experiment is to investigate how much the amount of fuel consumption and therefore emission production is reduced by Vessel Speed Reduction.

7.1.1 Design of experiment A

The experiments A can be written down in the following formulas. The variables can be found in the list of variables (see Appendix H).

A-a Experiment: asymmetrical variation of Pitch on engines port side and star board during phases sailing loaded and empty

$$U(t), H_p, N = f(M[1;2], S)$$

A-b Experiment: symmetrical variation of Pitch during phases sailing loaded and empty

$$U(t), N, v_w = f(S)$$

The two experiments A-a and A-b, described above were in practice combined into one experiment, called Experiment A; Table 7-1 shows their set-up. Experiment A consists of different phases where Pitch is changed and hold steady for a pre-defined time step. The table's columns PS and SB indicate the demand of Pitch during each experiment step. The value 75 means that 75% of the maximum Pitch capacity on one engine was requested. The speed the vessel stabilizes at, in each experiment phase needs to be measured and written down in the far right column.

Table 7-1 Outline Experiment A

200% of available capacity indicated means that 2 engines run at maximum capacity available

% of available capacity used	PS [%]	SB [%]	Duration	v_w
200	100	100	t	measure
175	100	75	t	measure
150	100	50	t	measure
125	100	25	t	measure
100	100	0	t	measure
50	25	25	t	measure
150	75	75	t	measure
175	87.5	87.5	t	measure
Total duration [min]			9t	

7.1.2 Execution of experiment A

In this paragraph the execution of experiment A on board and the adjustments to the design that were required are described

7.1.2.1 Time step and dredging phase

To gather as much information as possible this experiment should be performed and repeated for phases sailing loaded; sailing empty and discharging (see Figure 6-4). At this time Experiment A was only performed during one phase, because the experiment causes significant time loss compared to the normal operation of the 'Queen of the Netherlands'.

On board the phase 'sailing loaded silt' was identified as the most suitable phase for Experiment A. The reference measurements showed that the sailing period outside the port area normally takes around 90 minutes. The reference measurements also showed that it takes around 2 minutes for the vessel speed to become stable after a moderate change in Pitch. The time step was therefore determined at 10 minutes.

7.1.2.2 Series

The intention was to perform the two series of Experiment A under as much comparable circumstances as possible. It took a few days for a reasonably comparable sailing loaded phase to be scheduled for the second series. This was due to the large variations of tides in the port area and the relatively long dredging cycle in Ras Laffan.

The consequence of the relatively large period between both series was that a bunkering day fell in between them. Bunkering changes the weight and therefore, the water displacement of the empty vessel. Since experiment A1 was carried out with a fully loaded ship, this causes no problem for the interpretation of the results. The complete displacement of the dredging vessel is always maximised. This is in contrast to a container ship where the load stays constant for a longer period, which means that the displacement of the vessel alters after bunkering. For a dredging vessel the increased weight of the empty ship simply reduces the hopper capacity. The vessel displacement is always maximised for the expected tide with every loading phase.

7.1.2.3 Tide

A variation in tide influences the water depth and therefore the speed the vessel is able to reach. It also changes the volume of dredged material the hopper is able to carry without touching the sea bottom. Certain areas in the port are shallow; the vessel draught is tuned exactly for the passage of them. The Officers on the bridge monitor the tide at the expected hour of discharging and determine what the maximum draught of the ship can be. This effect is often more relevant for discharging than for dredging silt, since discharging often takes place in shallow waters. This is an example of why this experiment was chosen to be performed after dredging silt; the silt is discharged at open water where there is no restriction to the draught of the ship there.

7.1.2.4 Trim

It is impossible to avoid the fact that the trim of the ship might change. Experiences with the variation of trim on board (paragraph **Fout! Verwijzingsbron niet gevonden.**) have shown that trim changes can make a difference of up to 0.5 knots in vessel speed. A dredging ship changes its trim continuously during each dredging cycle, due to overflow. Therefore, it is impossible to keep this factor constant for two experiments. During normal operations the project planning also has to account for these deviations. Moreover, in advanced analysis the differences in trim could even be used to investigate the relation between trim and vessel speed.

7.1.2.5 Experiment sailing empty

It was impossible to perform experiments while sailing with an empty vessel. The scheduled mobilisation to the next project was postponed, which placed it outside the time limits of the experiments. Also the specific dredging cycle of Ras Laffan made that there were no substantial periods of sailing empty. The trip from the discharging area to the silt dredging area was too short; moreover it took place in shallow waters which makes sailing at full power impossible. The replacement from dumping area to dredging area was equally found too short. However, due to unforeseen circumstances there were a few trips without dredging silt. The data from these trips can be used as reference measurements.

7.2 Experiments Acceleration (B and C)

The acceleration of the vessel from zero or low speed to maximum sailing speed consumes high amounts of fuel. From other types of transportation it is known that especially accelerating as fast as possible is highly fuel intensive [[71]]. Experiments B and C were designed to investigate the influence of changes in the acceleration process on fuel consumption.

There are two types of the acceleration experiment, because the performances during acceleration are expected to be highly different for a fully loaded or an empty vessel. This paragraph discusses the design and execution of these two experiments.

7.2.1 Design of experiments B and C

The experiments B and C can be written down in one formula. The variables can be found in the list of variables (see Appendix H). The difference between the experiments is the phase in which they are executed.

B Experiment: Vary acceleration between phases dredging and sailing loaded
C Experiment: Vary acceleration between phases dumping and sailing empty

$$U(t), H_p, N = f(a, S)$$

The initial speed of the two experiments will be different: from zero to full speed (sailing empty) and from dredging to full speed (sailing fully loaded). The experiments were done after dredging sand and after dumping silt; both these activities take place outside the port area, where the water is relatively deep. Deep water allows the ship to accelerate maximally; in shallow waters, such as after discharging and dredging silt, the ship is never able to accelerate fully – because this will cause too much shaking on board the vessel.

Table 7-2 Schedule experiment B + C

Run	S	t	2t	3t	4t	5t
a	0	200				
b	-20	180	200			
c	-60	140	200			
d	-120	80	140	200		
e	-160	40	80	140	200	
f	-180	20	40	80	140	200

Table 7-2 shows the set up of experiment B and C. Run-a represents the acceleration like it is done normally. Run b till f represent the designed set-ups for the acceleration process – e.g. Run-c only demands 140% of available Pitch during the first time step and shifts to full capacity during the second time step. Since all operation is normally at full capacity it is impossible to increase the steering variables. Therefore, all values for S in Table 7-2 are negative compared to the reference situation.

Nominal experiment
Performing all 6 types of Experiment B and C would be highly time and labour intensive. Experiment B-e was chosen as nominal experiment to investigate the effect of changing operations management during acceleration. In the continuation of the report experiment B/C-e will be referred to as Experiment B/C. Multiple repetitions of this experiment were performed in order to determine the sensitivity of the measurements to changing circumstances. If results of the experiment with Run-e will be positive further experimentation can be performed with different run set ups.

7.2.2 Execution of Experiment B and C

In this paragraph the execution of experiments B and C on board and the adjustments to the design that were required are described.

7.2.2.1 Time step

The time step was determined from information gathered in reference measurements; dependent on the time it takes the vessel to reach full speed. Reference measurements showed that the Officer on duty normally holds the levers steady on each Pitch for a few seconds, before accelerating further. The levers are adjusted as soon as the Officer feels the ship is gaining speed; this allows more Pitch without overloading or too much shaking of the vessel. After approximately two minutes the Officer reaches maximum Pitch (Figure 7-1), after approximately five minutes the vessel reaches maximum speed (Figure 7-2). The time step for experiment B and C was set on two minutes. This size of time step guarantees a clear deviation from normal operations, but does not cause a great loss of time.

The design of the experiment also foresaw a variation of time step. In practice it turned out that with different Officers it was difficult to guarantee a constant change of Pitch. Officers mostly perform on tacit knowledge [[72]] – there are no standardized work methods – which makes each individual work method different. Altering the time step would reduce the reliability of the results. Therefore, the choice was made to focus on having sufficient series of the standard experiment.

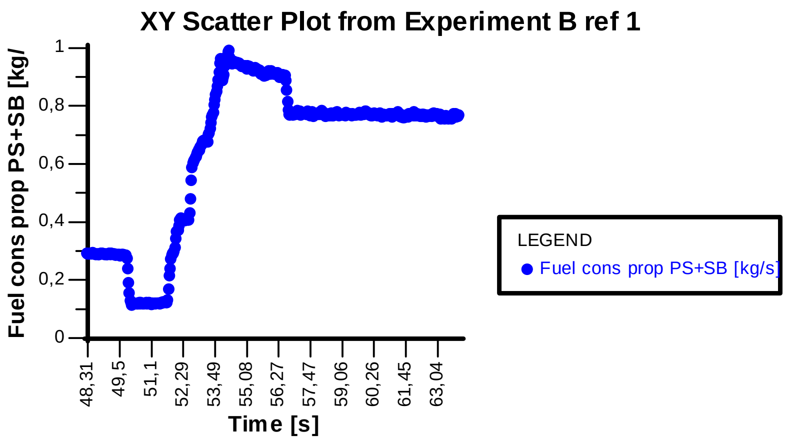


Figure 7-1 xy-scatter plot time versus fuel consumption of Acceleration process Experiment B ref 1 (Time is given in min not s)

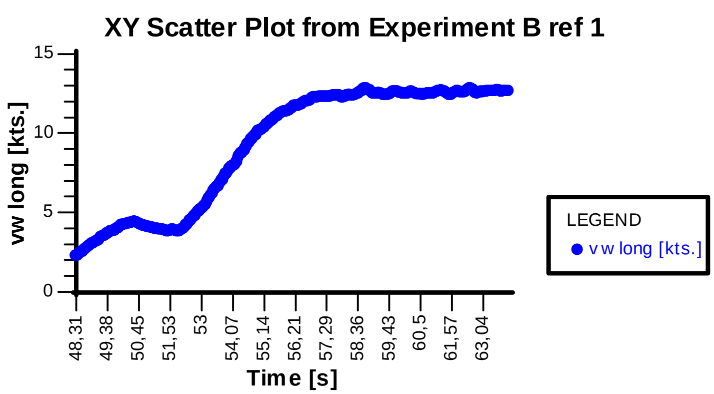


Figure 7-2 xy-scatter plot time versus vessel speed of Acceleration process Experiment B ref 1 (Time is given in min not s)

7.2.2.2 Series

The intention was to repeat experiment B with small positive and negative variations; the schedule for this can be found in

Table 7-3 shows the nominal experiment schedule. Experiences on board showed that it is impossible to perform measurements with such small variations. The levers cannot be adjusted accurately enough to guarantee such variations. A difference between Pitch 90 and 92 can hardly be identified on the levers. Natural variation in the work method of Officers already caused larger variations. Therefore, more standard series were performed to have as much reference of that as possible, rather than decreasing reliability further by creating additional variation.

Table 7-3 Experiment schedule nominal experiment B + C

Run	S	t = 120s	2t = 240s	3t = 360s	4t = 480s	5t = 500s
1	-124	76	134	152	200	200
2	-120	80	140	160	200	200
3	-116	84	146	168	200	200

Several changes in project planning foiled the multiple repetition of experiment C. E.g. due to bunkering and human errors in location planning silt trips were adjourned for a few days. The experiment was completed once without the computer being installed properly. Problems with the engine and computer system prevented full acceleration from being possible on the next few trips.

The results of experiment B have been used to compensate this. Several series of experiment B were completed successfully and provide most of the information. The data that are available for experiment C can be compared to that. The difference in vessel speed between experiment B and C can also be determined from reference measurements, so the general result of experiment C will still be available.

7.3 Reference measurements dredging (D) and discharging (E)

The phases dredging and discharging were only monitored for reference and no experiments were performed, since the dredging phase contains too many variables and the influence during the discharging phase would be too directly visible in the project performance output. If results of this research turn out favourable for the sailing phases, recommendations for further research will be done to start experimentation in these phases.

7.3.1 Design of reference measurements D and E

The experiments D can be written down in the following formula. The variables can be found in the list of variables (see Appendix H).

D Reference measurement phase dredging

$$U(t), N, ((v_{d.gps}, v_{d.w}) - v_p), \rho = f(S)$$

For the dredging phase only reference measurements were foreseen in this phase. Of all phases the dredging activity is calculated the most careful. Appropriate speed is required to realize maximum production; a Pitch change directly influences production. Private conversations on board also showed that this is the phase where Officers are most proud of; the optimal balance cannot be learned from books but is stored as tacit knowledge [72] with the life-time experienced.

Further knowledge about the relations between speed and production needs to be gathered before effective experiments can be designed for this phase.

E Reference measurements phase discharging

The experiment E can be written down in the following formula. The variables can be found in the list of variables (see Appendix H).

$$U(t), N, \rho, v_p, V = f(S)$$

In paragraph 2.7.1 numbers showed that next to sailing, discharging via pipes to shore is an energy intensive activity. Reductions that could be realized in this phase would be substantial. Discharging is always performed at maximum capacity. Therefore the schedule of experiment A could be followed to investigate the effects of reduced power on discharging production.

In practice, influencing this phase was too delicate an issue for the project operators. The required material speed and pipe length are calculated very carefully, before the project; any changes are directly visible for the client. Also if power drops below a certain level it is no longer possible to push the material through the full length of the discharging pipe. Therefore the decision was made not to perform experiments in this phase but only monitor the performances. Since circumstances are predominantly constant in this phase the reference measurements will provide valuable information on the consumption of fuel and production of emission.

7.4 From experiments to results

In this chapter a description has been provided of the different trials: how choices were established and what possibilities were available. Consequently the gathered data of the trials need to be processed. The next chapter continues with the description of the trial process; it contains a description of the data analyses and formulates the results of the experiments.

8 Results

This chapter provides a summary with highlights of the results of the trials. Given the large amount of data that were gathered on board, the number of analysis that could be performed is endless. Time restrictions and scope of this research make it impossible to perform an exhaustive analysis of results.

The choices for analysis were based on multiple selection criteria (described in hierarchical order): I) highest expectations for results – in which dredging phase do we expect to be able to reach the greatest effect II) highest reliability of data – during trials not all variables turned out to be reliable, if alternatives are available the most reliable variable has been picked and III) best possibilities for analysis. If multiple variables are available and found to be reliable the variables that provide best possibilities for analyses are used.

The chapter starts with the explanation of how the output variables together form the objective function of the research. Then in paragraph 8.2 the theoretical relations to transfer SCADA output into desired output variables are discussed. Paragraph 8.3 treats the reference measurements; the fuel consumption loggings have been used to calculate the value of the performance indicators - such as, actual amount of gaseous emission - caused by the ship while sailing at maximal capacity. The complete data from the reference measurements per phase provide an updated overview – which can be used by the dredging department when calculating works – of vessel performances during standard operation.

Finally – in paragraph 8.4 – the empirical relations derived from the results of experiments are discussed. The log data have been observed and analysed to find relations between the fuel consumption and operational behaviour on the vessel. After this the data from the experiments have been analysed further for specific relations about the influence of changes in operations management on the output variables.

8.1 Objective function

The objective function of this research defines the trade-off between maximum speed and minimum emission. The result of the objective function provides an overview of the costs and benefits caused by operational change. The meaning of variables can be found in the list of variables (see Appendix H).

The objective function to minimize consists of three separate objective functions for the different types of costs:

1. costs of emission
2. costs of operational time loss or gain
3. costs of fuel

Total Costs = Costs emissions + Costs operational + Costs fuel =

$$C_{em} + C_{op} + C_f$$

$$\min_{N} C_{tot} = \min_{N}\left(C_{em} + C_{op} + C_f\right)$$

Costs can be either negative or positive. The total costs consist of several subparts which can be adapted according to circumstances; e.g. the price of emission is not only the price of taxes or subsidies but also the price that the client is willing to pay the contractor to prevent emission. In the boxes below the three cost equations are shown in more detail.

Emissions costs:

$$C_{em} = \frac{m_{em}^{g\text{-}out}}{V} P_{em}$$

$$C_{em} = \frac{m_{CO_2}^{g\text{-}out}}{V} P_{em.CO_2} + \frac{m_{SO_x}^{g\text{-}out}}{V} P_{em.SO_x} + \frac{m_{NO_x}^{g\text{-}out}}{V} P_{em.NO_x}$$

$$C_{em} = (P_{em}) \frac{f_{m_{em}^{g\text{-}out}}(U)}{V}$$

$$f_{m_{em}^{g\text{-}out}}(U) = f_{m_{CO_2}^{g\text{-}out}}(U) + f_{m_{SO_2}^{g\text{-}out}}(U) + f_{m_{NOx}^{g\text{-}out}}(U)$$

$$f_{m_{CO_2}^{g\text{-}out}}(U) = \left(\frac{m_{CO_2}}{m_C} x_{C_f}\right) U$$

$$f_{m_{SO_2}^{g\text{-}out}}(U) = \left(\frac{m_{SO_2}}{m_S} x_{S_f}\right) U$$

$$f_{m_{NO_x}^{g\text{-}out}}(U) = k_1 \; U$$

$$U = k_2 \, N$$

Operational costs:

$$C_{op} = \frac{H}{V} P_{op}$$

$$C_{op} = P_{op} \frac{g_H(N)}{V}$$

Fuel costs:

$$C_f = \frac{U}{V} P_f$$

$$C_f = P_f \frac{h_U(N)}{V}$$

Degrees of freedom are time required (H) and fuel consumption (U) which are influenced by steering variable power (N). For SO_x and CO_2 mass emission produced $(m_{em}^{g\text{-}out})$ is directly related to fuel consumption (U). NO_x emission is related to power (N) and engine specifications which were determined during engine shop trials (see Appendix F).

$$H = \frac{D}{v_w}$$

$$v_w(V) = \mathrm{k}_3 S$$

$$N = \mathrm{k}_4 S^3$$

The actual vessel speed realized is a linear function of Pitch. The slope of this function depends on circumstantial factors, e.g. the draught (or water displacement) of the vessel. The value of k_3 will vary for different hopper volumes. The values of the constants k_3 and k_4 was determined in Experiment A. Experiment B and C aim at finding the relation between acceleration, vessel speed and fuel consumption.

8.2 Model for translation of data

For most factors the SCADA output does not provide variables that are directly usable as the desired output factors, e.g. SCADA does not automatically provide the factors fuel consumption or emission production. These factors can be calculated based on theoretical or empirical relations. To allow direct calculation of these factors in the future the relations have been saved in a standard spreadsheet in Microsoft Excel. The standard spread sheets have been used for the calculations of results of this research, but can serve as a model in the future. Standard SCADA output from future experiments can be translated to workable factors automatically with these model spread sheets.

In this paragraph the translation step between SCADA output and desired output for performance indicators is described. The different relations, their theoretical basis and how they were used in this research are explained.

8.2.1 Calculation fuel consumption

The available data offer three possible methods for calculating the fuel flow. The most accurate is via the inlet flow of the injection pump. The variable 'Fuel rack' (see Appendix H) measures the position of the injection pump for each injection. By multiplying this position with the surface of the fuel injection valve the fuel flow can be determined. Integration of this value over a longer time period will provide the total fuel consumed during this period. At this moment the exact surface of the fuel injection valve is unknown; therefore it is currently impossible to use this method.

The second method - which can be realized without further need of data but is somewhat less accurate - is via the measurements of delivered power from the propellers and generators. it is possible to estimate fuel consumption based on specific fuel consumption from engine shop trials carried out by engine manufacturer Wartsila in 1997 prior to the construction of the vessel in 1998 (see Appendix F). The results can be checked for reliability by comparing the calculated numbers with the measured fuel consumption on day basis. This only serves as extra check since this the daily fuel consumption measurement is an unreliable number, measured in an inaccurate way with a possible variation of +/- multiple MT of fuel.

A third method proposed is the integration of the fuel rack position and comparing it to measured fuel consumption per day. This method uses only one empirical variable: the variable fuel consumption per day is very much unreliable with a possible variation of +/- MT of fuel.

Table 8-1 below provides a summary of the different methods for calculation and the criteria that have been used to choose the method most appropriate for this research.

Table 8-1 Multi-criteria comparison of methods for determining fuel consumption

	Fuel inlet	Power consumption	Fuel rack
All information available	No	Yes	Yes
Number of empirical variables	2	2	1
Accuracy of empirical variables	High / moderate	Moderate / low	Low
Analysis method	Difficult	Easy	Average

The level of accurateness in the analysis and recommendations of this research is limited. Recommendations show a possibility of effect and results but do not provide specific numbers. Therefore, the second method is sufficient to meet the requirements of the research. Using the power consumption method for calculating fuel consumption from delivered power does not significantly decrease the accuracy of results further. If follow-up research requires more accuracy to further analyze a feasible region the exact fuel inlet should be determined. The continuation of this paragraph will explain the chosen method of calculation more specifically.

8.2.1.1 Calculation of fuel consumption from power delivered

For this calculation the measured specific fuel consumption at 85% load is used. The specific fuel consumption is given in [g/kWh] which can be translated to [kg/kJ]. The loggings of delivered power are given in [kW]. Multiplying these two units provides the fuel consumption in [kg/s].

Constants:

Specific fuel consumption	HFO	185,9	[g/kWh]	85% load
[g/kWh] → [kg/kJ]	HFO	5,16389E-05	[kg/kJ]	85% load

8.2.1.2 Translation to fuel consumption per hour or day

SCADA delivers output of power in [kW]; the translation to fuel consumption therefore provides values in fuel mass per second. For the estimation of full cycles, numbers about the average fuel consumption per operation hour is desired. To calculate how much fuel has been consumed over a longer period of time – e.g. a complete phase of the dredging cycle - it is possible to determine the surface of the region in the ty-plane bounded by the graph $f_t(U)$ between t=a and t=b. The surface of this region can be determined by the integral $\int_{t_i}^{t_0} f(U)dt$.

To simplify this calculation it is equally possible to calculate the average – of all two second loggings – within a certain time period and multiply this number by the elapsed time. This method touches the method of numeric solving that mathematical software uses but is somewhat less accurate. Nevertheless, the method is sufficient for this research, since the accurateness of measurements and found relations in this research is quite low and the purpose of this research is to provide general recommendations for a feasible direction of solutions.

8.2.2 Calculation of emission factors

By multiplying the amount of fuel consumed with the emission factors the translation step to mass of emission produced is performed. In this paragraph the determination of the value of the emission factors is explained.

8.2.2.1 Fuel specifications

Before emission factors can be used it is important to determine the composition of the consumed fuel. The calculations of this research are based on the consumption of HFO 380, which is the most commonly used fuel on the 'Queen of the Netherlands'. The carbon / hydrogen ratio needs to be known as well as the sulphur content of the fuel.

Accurate specifications about the C/H ratio of the fuel in bunkers at the time of the trials are not available at this moment; therefore, estimations are required. Appendix G provides general values for fuel specifications used at Boskalis. From the general fuel specifications the maximum weight fraction of sulphur and the maximum volume fraction of water in the fuel are known. With these values and an assumption about the C/H ratio we are able to estimate the weight fraction of Carbon. HFO is generally a mixture of different types of hydrocarbons with different C/H ratios. The C/H ratio of these mixtures generally lies between 6 and 8 [73]. For this research a C/H ratio of 7.5 is assumed. Combining this ratio with fuel specifications of Boskalis provide the following weight percentages which can be used for further calculations in this research (see Appendix G):

Estimation of weight percentages:

$x_C^f = 86\ \%$
$x_H^f = 11\ \%$
$x_S^f = 3\ \%$

Using estimations for the fuel composition does not affect the accurateness of assumed relationships for fuel consumption versus speed. The estimations only influence the value of the output amount of emission; the factors used to assume relations are not affected. The relations enable future calculation of emission with user-defined information about fuel composition.

8.2.2.2 Equations for emission production

After the fuel specifications tell how much molecules or weight of one element goes into the engine, factors are required to calculate the production of emission. For CO_2 and SO_x the factors are based on the combustion reactions. For NO_x the factor was determined in engine shop trials Appendix F.

A number of equations is used to calculate the produced emission from the fuel specifications and consumed fuel. If emission need to be expressed in parts per million on Volume basis [ppmV] – which is a common unit for emission expression – the kilo mol-ratio can be used to calculate the number of molecules emission gas produced per kg of consumed fuel. The mass ratio equation provides the mass of emission gas produced when one kg of fuel is consumed. The shown equations are for the production of CO_2. For the calculation of SO_x the calculations are identical after replacing the subscripts $_C$ by $_S$.

Kmol ratio:

$$\mathrm{nr}_{CO_2}^{\text{g-out}} = \frac{x_{C_f}}{M_C}\ [\text{kmol/kg fuel}]$$

Mass ratio:

$$\mathrm{mr}_{CO_2}^{\text{g-out}} = \left(\frac{M_{CO_2}}{M_C}\right) x_{C_f}\ \ [\text{kg/kg fuel}]$$

In this research the mass ratio will be used for further calculation, because the objective function requires values to be specified in [g/m^3]. The text box below contains the complete relations calculated based on the estimations of fuel specifications (CO_2, SO_x) and the engine shop trials (NO_x).

The estimated weight percentages provide the following equations for this research:

CO_2:

$$f_{m^{g\text{-out}}_{CO_2}}(U) = \left(\frac{m_{CO_2}}{m_C} x_{C_f} \right) U = k_3 U = 3{,}153333U$$

SO_2:

$$f_{m^{g\text{-out}}_{SO_2}}(U) = \left(\frac{m_{SO_2}}{m_S} x_{S_f} \right) U = k_4 U = 0{,}06U$$

NO_x:

$$f_{m^{g\text{-out}}_{NO_x}}(U) = k_1 U = k_2 N = 0{,}00000334\, N$$

8.2.2.3 Produced emission

The exact amount of emission can vary for each second. Over a longer period emission can be calculated by multiplying the average value, using the same method as for fuel consumption (paragraph 8.2.1.2).

8.2.3 Calculation of production

The production can be calculated using the output material density (ρ) times production speed (v_p) minus the material which is dissolved in the water, continuously overflowing the hopper. The relation production versus fuel consumption is not analyzed further in this research so this calculation will not be performed here. The production numbers from the Boskalis database are well researched so can be used to calculate the 'Performance Standard Rate' of emission.

8.3 Results reference measurements

In this paragraph the results of the reference measurements are presented. This provides an overview of the actual fuel consumption and emission during standard operation of the 'Queen of the Netherlands'. The results in this paragraph can be used for project planning by the dredging department.

8.3.1 Reference maximum situation

To determine a representative moment for standard operation the operations were monitored manually. At time of the test period the ship was in need of some reparations; this affected the maximum power request possible. Additional power request causes too much shaking for the staff and equipment on board. Because of this reason moments with maximum engine load during the trial period were scarce.

On October 20 2007, 15:51 – 16:18, the maximum speed – as observed during the trial period - was held reasonably steady. The data of this period have been analyzed and can be used as reference for the maximum capacity of the vessel. Figure 8-1 shows the fuel consumption of the vessel during maximum operation.

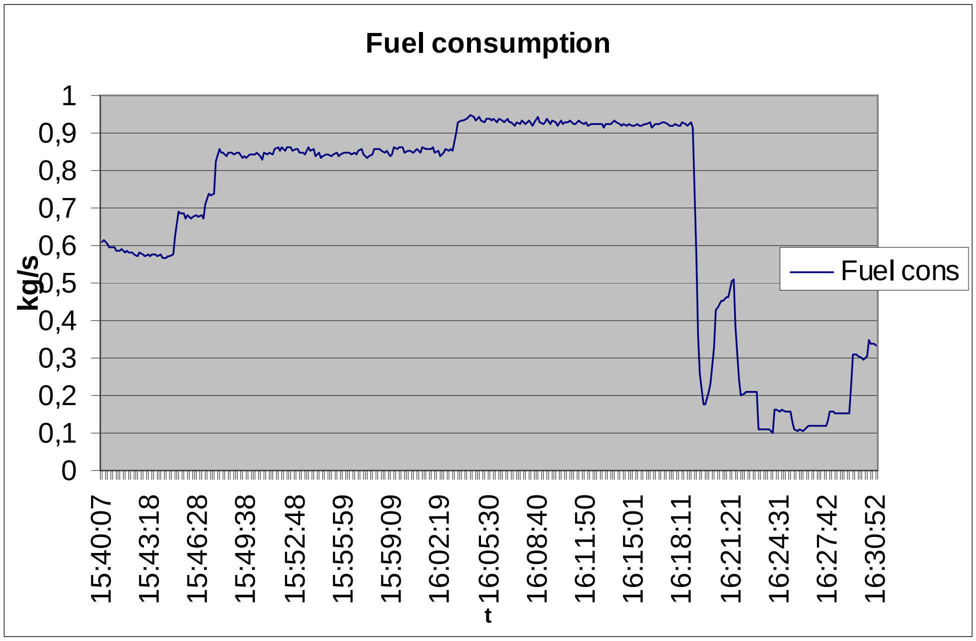


Figure 8-1 Line graph of fuel consumption caused by vessel propulsion during operation at maximum load

Figure 8-2 displays the vessel speed realized during the maximum situation on October, 20. Note: that at time 16:04 the fuel consumption makes a step (because further Pitch request is possible). The vessel speed on the other hand only makes a small increase during this time period.

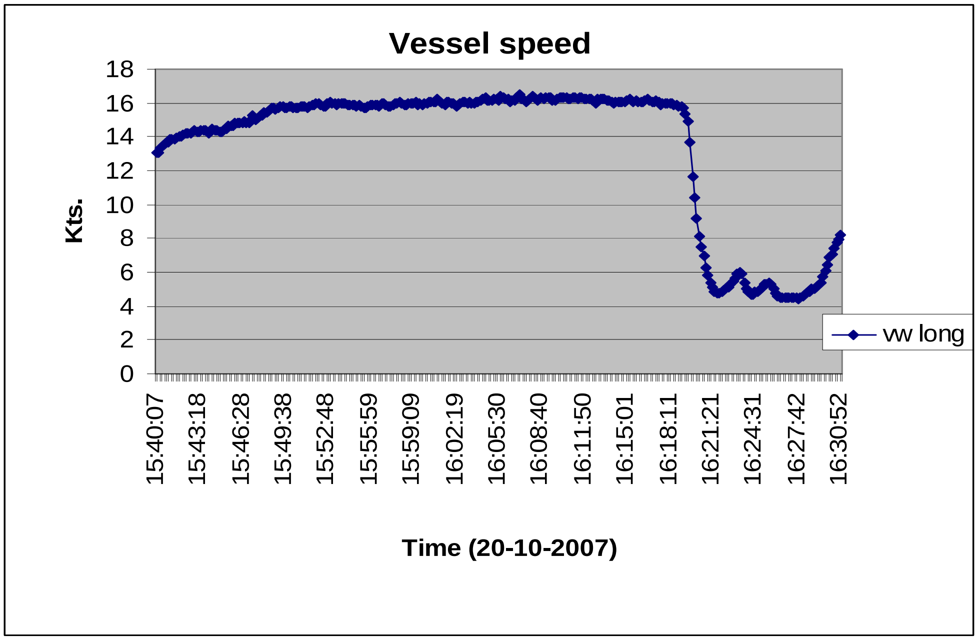


Figure 8-2 Line graph of vessel speed during operation at maximum load

In the box below the maximum values for fuel consumption, emission and vessel speed are given. If the vessel is fully loaded and performing at maximum load one meter of sailing distance between dredging area and discharging area causes 0.39 kg of CO_2 emission. A sailing distance of 10 nautical miles would cause over 7 ton of CO_2 one way.

In the text box below the coefficients are given that can be used for planning calculations. values are for calculation; significant numbers should be limited for final predictions

Maximum values for reference:

$\max U_{\text{prop}} = 0.91$ [kg HFO/s]

$\max m_{CO_2}^{g\text{-}out}$ 2.87 kg [CO_2/s]

$\max m_{SO_x}^{g\text{-}out}$ 0.055 kg [SO_x/s]

$\max m_{NO_x}^{g\text{-}out}$ 0.055 kg [NO_x/s]

$\max v_w = 16$ kn

0,056 [kg HFO/s per kn]

8.4 Experiment results

In this paragraph the results of the performed experiments and the empirically determined relations are described. Per empirically found relation result, critique and further recommendations are discussed.

8.4.1 Experiment A

During this experiment the Pitch (position of the blades of the propeller through the water) was varied several times and held steady for ten minutes each time. The purpose was to find the influence of the variation of Pitch on the vessel speed. The changes of Pitch were performed straight after each other - instead of each Pitch demand in a new cycle - so that circumstances would be as constant as possible. However it is impossible to keep circumstances completely constant; e.g. within one sailing distance the water depth constantly increases when sailing further away from shore. These variations need to be considered when interpreting the results.

In Paragraph 7.1 the planning of this experiment was described; Table 8-2 shows the final setup of the experiment, as it was performed on board. The first column shows which percentage of available capacity the sum of Pitches PS + SB represents; the columns PS and SB show the actual requested Pitch values. A higher load than Pitch PS 91 and Pitch SB 95 would overload the engine and / or cause too much shaking of the vessel.

Table 8-2 Experiment A schedule

% of available capacity used	PS	SB	T [min]	v_w
150	72-76	72-76	10	measure
175	60	60	10	measure
150	45	45	10	measure
100	88-89	0	10	measure
125	89	25	10	measure
150	89	50	10	measure
175	89	75	10	measure
200	91	95	5	measure
Total duration [min]			90	

Figure 8-3 shows the complete results for the fuel consumption (caused by the propulsion of the vessel) and the vessel speed of experiment A2. The experiment starts at time 600; each step – visible on the fuel consumption line – represents a change of Pitch. Experiment A1 provides a comparable graph. The hopper load during experiment A1 and A2 was approximately 18000 m^3.

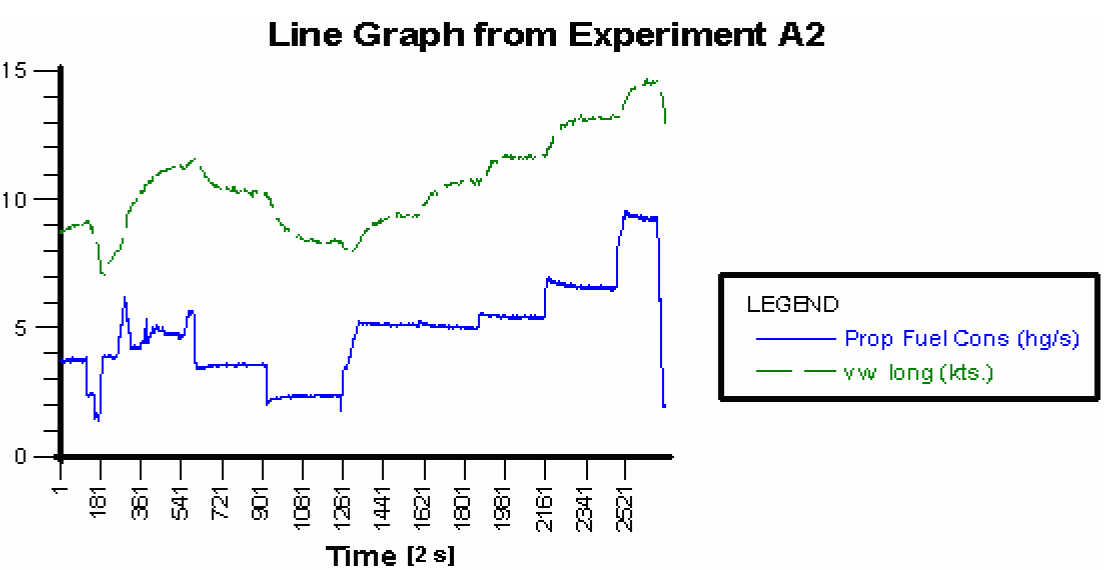


Figure 8-3 Line graph Experiment A2 fuel consumption propellers and vessel speed

8.4.1.1 Relation Pitch versus Vessel speed

Theoretically the relation between Pitch and speed of the vessel should be linear. A change in the position of the blades should cause a proportional change in speed. This leads to the following hypothesis:

$\text{HYP}_0 : v_w(V) = \text{k}_3\, S$

Figure 8-4 shows the empirical relation between Pitch and vessel speed during Experiment A1. The dots represent the stable vessel speed that is reached after each Pitch change. The red dots show the symmetrical variation of PS and SB. The blue dots the variation of Pitch SB from 0 to 95 and Pitch PS constant at 89. Fitting the dots of the same colour with a linear relation shows a positive result.

The value of the speeds the vessel reaches for each Pitch depends on the load of the hopper, so the vessel displacement. Lines with identical Pitch variation but different vessel displacement would run parallel. The two lines in this figure cross each other in the end where Pitch variation of the red line also becomes symmetrical.

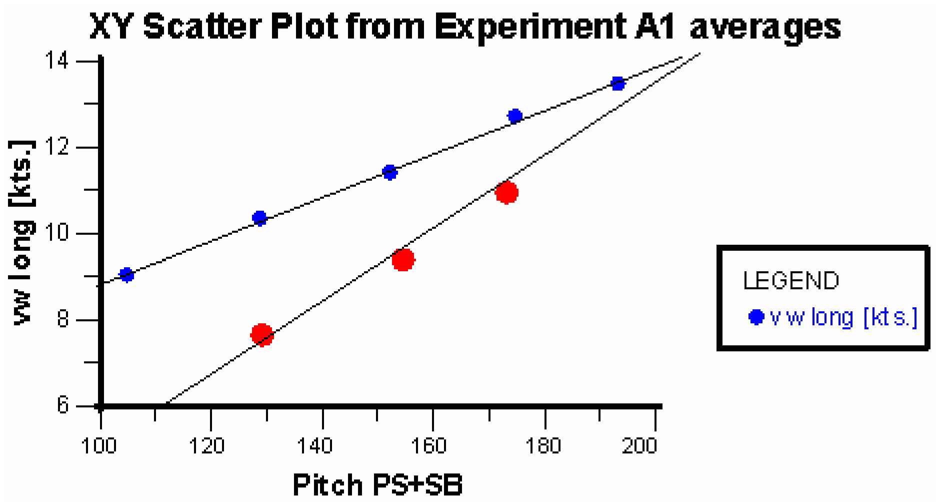


Figure 8-4 Relationship Pitch and vessel speed (blue dots symmetrical Pitch PS and SB; red dots asymmetrical Pitch PS and SB)

8.4.1.2 Relation Pitch versus fuel consumption

The amount of power - and therefore fuel consumption - required to reach a certain Pitch (and vessel speed) is not linear. Roughly said this is because of increasing resistance; when the angle of the propeller increases more and more work is needed to keep the propeller velocity even. Therefore, the engine has to deliver much more power to realize a small change in propeller angle.

When making an economic calculation about fuel use and speed one could presume the relation between power and propeller velocity can be expressed as [74]:

$$N = \text{k} * rpm^3$$

Propeller velocity [rpm] for the 'Queen of the Netherlands' is set constant at 500 rpm. Therefore, the following hypothesis is formulated:

$$\text{HYP}_0 : N = \text{k}_4\ S^3$$

Figure 8-5 and Figure 8-6 show the amount of power delivered at different Pitch during Experiment A1. When little Pitch is demanded the delivered power is significantly lower. This can be seen in the Pitch Star Board graph (Figure 8-5); which shows the relation between Pitch and power delivered or fuel consumption; the development of the values is clearly exponential.

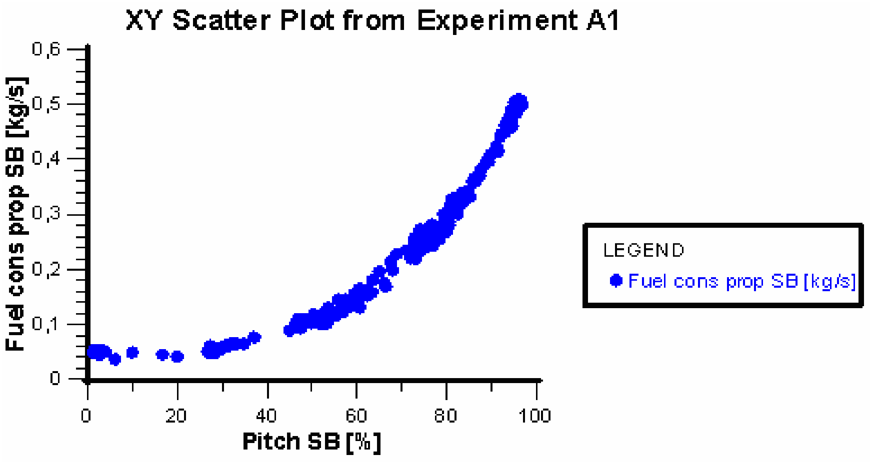


Figure 8-5 xy-scatter plot of Experiment A1 Pitch SB versus fuel consumption

As discussed in Paragraph 6.6.2 the loggings of Pitch PS are not reliable; values only vary between 20 and 70%, while human monitoring indicates they should vary between 0 and 100%. For this reason the graph in Figure 8-6 does not provide a clear development. When Pitch comes above 50% the values become spread and identical values of Pitch give large deviations for Power delivered vales. Loggings of Power on port side show that the power request corresponds to the values of star board, so star board values are the most reliable.

After the detection of this default alternative variables were sought and the Pitch was directly measured from the lever demand from that time (see Paragraph 6.6.2). Unfortunately, this problem was only noticed after the execution of Experiment A1. This means that for experiment A1 there are no values available for Pitch. Unlike for other experiments where the Pitch was always varied symmetrically this does cause a problem at Experiment A. For Experiment A1 human observations of Pitch PS demand will have to provide.

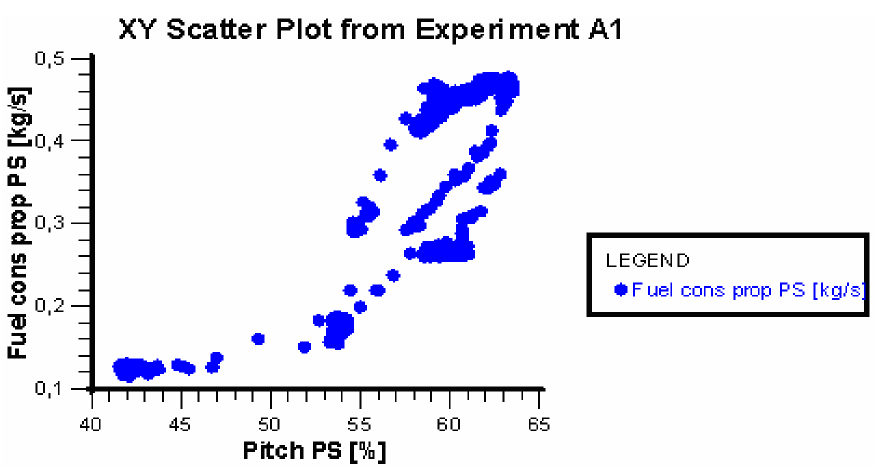


Figure 8-6 xy-scatter plot of Experiment A1 Pitch PS versus fuel consumption

At higher load the internal efficiency of a diesel engine should be higher; this is confirmed by the engine shop trials in Appendix F. Therefore, it is less advantageous to use the engine at low power. However, this influence is small and becomes relatively smaller when the influence sketched above becomes larger – so at higher Pitch. The strong effect of this relation is observed when observing the tests where Pitch PS is below 50%. Below 50% values the fuel consumption practically does not decrease for lower Pitch; the effect of the lower power request is counterbalanced by the decreased internal efficiency of the engine.

8.4.1.3 Relation vessel speed versus fuel consumption

In this paragraph the relations between Pitch versus vessel speed and Pitch versus fuel consumption are combined into one relation – realized vessel speed versus fuel consumption. Figure 8-7 and Figure 8-8 show the amount of fuel consumed versus the realized stable vessel speed. Figure 8-7 also shows the requested Pitch for each dot. The figures show that the required fuel consumption increases faster at higher speed. Note that the outlying values are the results of the asymmetrical variation of Pitch PS and SB; they form a separate curve from the values with symmetrical Pitch PS and SB.

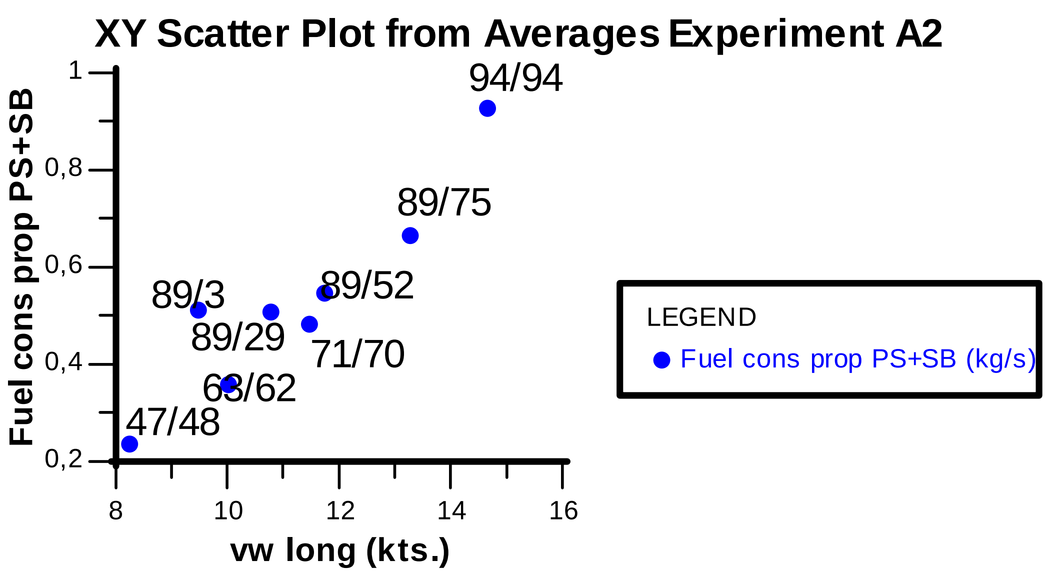


Figure 8-7 xy-scatter plot of stable speed experiment A2 (Pitch/Pitch demanded is displayed for each point plotted)

Figure 8-8 shows the stable vessel speed the vessel reaches – for both series of experiment A – and the fuel consumption caused by the propulsion at that time. The realized vessel speed is somewhat lower for experiment A1 than for Experiment A2 for all Pitches. The difference between the two experiments says something about the accuracy of the predictions of vessel speed. There can be several explanations for this discrepancy. Volume of the hopper and displacement of the vessel seem to differ little. Different water depth can be an explanation, when a ship is running in deeper waters it should theoretically be possible to reach higher speeds. This variable was not available in the SCADA system and could be monitored only manually on board. Differences in these observations do not seem substantial over the whole period but it is possible that these have caused significant differences. The difference between experiment A1 and A2 shows that the results of this experiments cannot be used for exact vessel speed planning. To qualify for exact speed planning further research is required. This research facilitates the identification of the feasible region for VSR. Once a region is identified as feasible under pre-defined circumstances further research should provide data for exact speed determination.

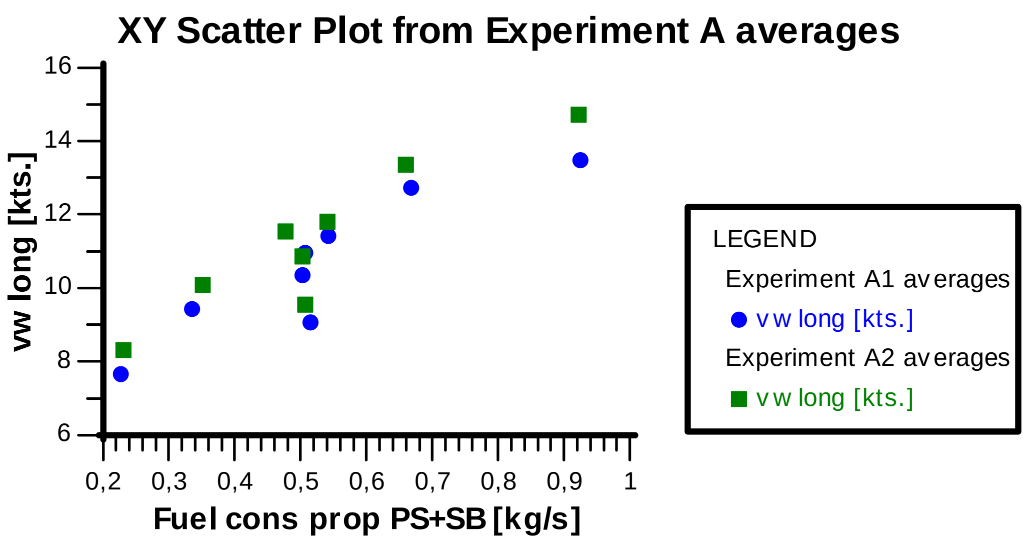


Figure 8-8 xy-scatter plot of stable speed experiment A

8.4.1.4 Specific fuel consumption per Pitch

The optimal balance between power required for basic operation and power required for increased Pitch can be found by analyzing the fuel consumption relatively to the speed of the vessel. In Table 8-3 the amount of fuel consumption per second that is responsible for one kn of vessel speed is displayed. This number is by far the lowest at a Pitch ratio of 47/48, 0.028 kg/s per kn. At maximum load the ratio is highest, more than 0.063 kg/s per kn. This follows naturally from the graph of Figure 8-7: when changing from Pitch 47/48 to Pitch 94/94 the velocity of the ship will not even double while fuel consumption almost quadruples. For the asymmetrical variation of Pitch the number is equally lowest for a SB variation around 50.

Table 8-3 Fuel consumption / speed ratio for different pitch demands

Pitch / Pitch	$\frac{U_{prop}}{v_w}$ symmetrical Pitch	$\frac{U_{prop}}{v_w}$ asymmetrical Pitch
47/48	0,028185	
63/62	0,035233	
71/70	0,041628	
89/3		0,053516
89/29		0,046713
89/52		0,046157
89/76		0,049757
94/94	0,062919	0,062919

At very low Pitch, the engine still has to work relatively much to reach the required velocity of 500 rpm; this could be seen as power needed for basic rotation and resistance. The increase in speed of the vessel that low Pitch generates is relatively small. At intermediate Pitch the basic power needed becomes less influential while the extra power needed to achieve the required Pitch is still reasonable. At high Pitch the influence of the extra power required for the increased angle of the propeller becomes dominant over the effect of vessel speed increase and - with respect to fuel consumption - it becomes less advantageous to further increase Pitch.

8.4.1.5 Conclusions Experiment A

Experiment A shows that indeed large reductions in fuel consumption can be realized when reducing Pitch from maximum. Experiment A did not indicate any favourable results for operation at asymmetrical Pitch. The extra fuel required to have one engine run on low power makes other favourable results neglect able. If operation at one engine is desired the other engine should be completely shut down and both generators should be powered by the first engine. The results show that this is indeed a good method for fuel reduction. However this method is less efficient than sailing on two engines at 60%, the consumption at 60% is 0.16 [kg/s] per engine, so below 0.4 [kg/s] in total. One engine at 90% consumes 0.4 [kg/s] (see Figure 8-5) while two engines at 60% realize more speed (see Figure 8-7).

What will be the optimal Pitch request of a work will depend on circumstances and project goals. To enable calculation of the optimal Pitch request for specific work circumstances the relations of this chapter are included in to a spread sheet model that functions as decision-making tool. This model will be introduced in Chapter 9.

8.4.2 Experiment B and C

The second type of experiments relates the acceleration phase of the vessel. These experiments consist of two types:

- Experiment B where the ship is fully loaded with silt and accelerates to go to the discharging area.
- Experiment C where the ship is empty after dumping its silt and has a small distance to sail to the dredging area.

8.4.2.1 Correction of incorrectly logged variable

Figure 8-6 showed that loggings of Pitch PS are not correct. For the first series of experiments B and C there are no data available for Pitch lever demand. During these experiments Pitch was always varied symmetrically. Therefore, the values of Pitch SB can be multiplied by two in order to get an approximation of total Pitch PS + SB.

8.4.2.2 Relation acceleration versus vessel speed

This experiment was carried out to investigate the effect of changing the operational behaviour during the acceleration phase on the fuel consumption and the duration of this phase. The hypothesis states that a change in operational behaviour causes a significant difference in fuel consumption and emission.

$$\mathrm{HYP}_0 : \textit{exp.Bref} \text{ is significantly different from } \textit{exp.B}$$

Figure 8-9 shows the vessel speed curve during the different experiments. The data output of reference experiment Bref2 was not suitable for comparison. This paragraph investigates whether reference experiment Bref1 is significantly different from experiments B1 – B4.

Experiment B ref1 (light blue line) reaches maximum speed 92 seconds before the average moment the experiments reach maximum speed. The complete acceleration process (from 4 – 12 kn.) of Bref1 takes (row250 – row118) 264 seconds. The acceleration process of the experiments B1 – B4 takes on average (row270 – row92) 356 seconds.

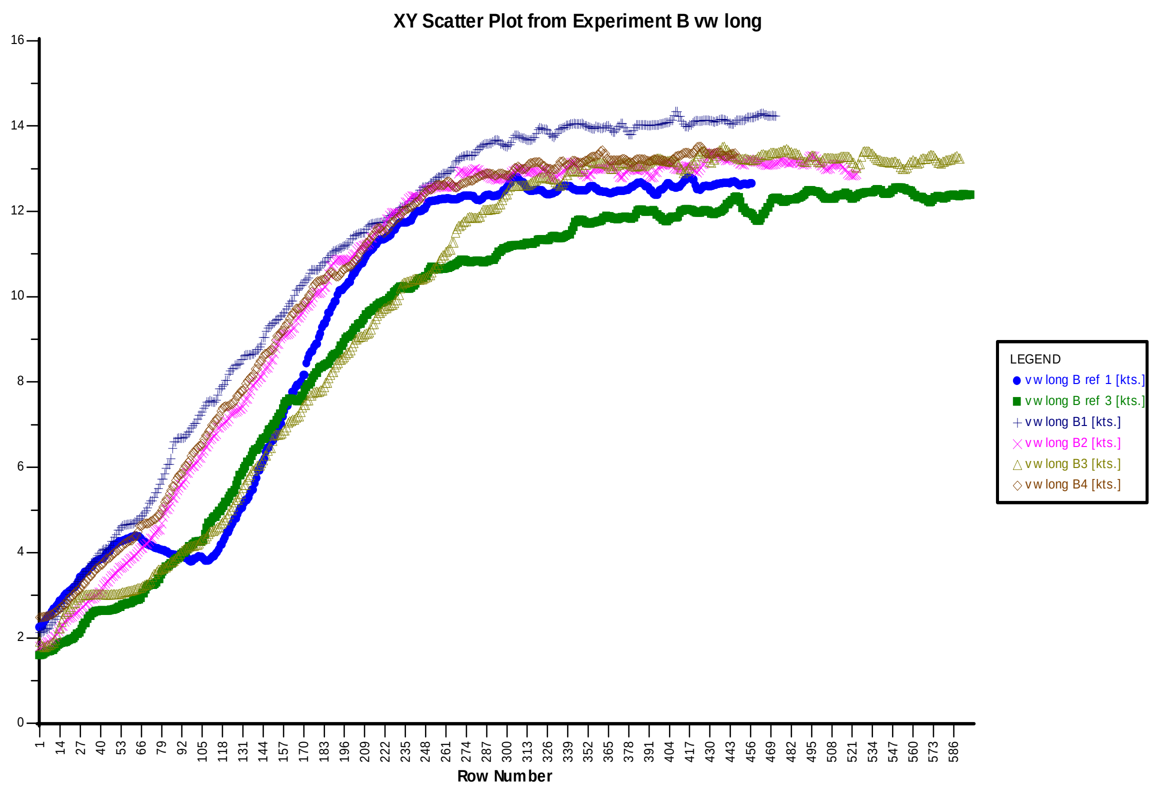


Figure 8-9 Vessel speed curves in [kn.] for experiment B (row number = time [2s])

Average speed multiplied by time of acceleration process (8 * 264) + time difference (92) * max speed (12) shows how much distance has been bridged in this period. Versus (8.5 * 356) Comparing these two values will give how much time is gained by faster acceleration. Experiment Bref1 covers 0.89 nautical miles in 356 seconds while the average of B1 – B4 covers 0.84 nautical miles. The next step is to check whether the fuel consumption curves differ significantly.

8.4.2.3 Relation acceleration versus fuel consumption

The fuel consumption curves of experiment B are shown in the figures below. Figure 8-10-a and b show that the light blue line of Experiment Bref1 runs almost vertical. After 50 seconds (t150 – t100) the fuel consumption the line reaches maximum fuel consumption. The lines of experiment B1 – B4 run stepwise in accordance with the experiment steps (see Table 7-3). Note that also the line of experiment Bref3 runs stepwise.

To compare the total fuel consumption during the acceleration period the average fuel consumption is required. The average fuel consumption for experiment B1 – B4 during the acceleration period is approximately 0.5 [kg/s]. The average fuel consumption for Bref 1 is also 0.5 [kg/s].

Average fuel consumption multiplied by time of acceleration process (0.5 * 264) + time difference (92) * max Ufuel (0.95) shows how much fuel was consumed during this period in total. The difference between 219 kg and 178 kg of fuel during the complete acceleration period.

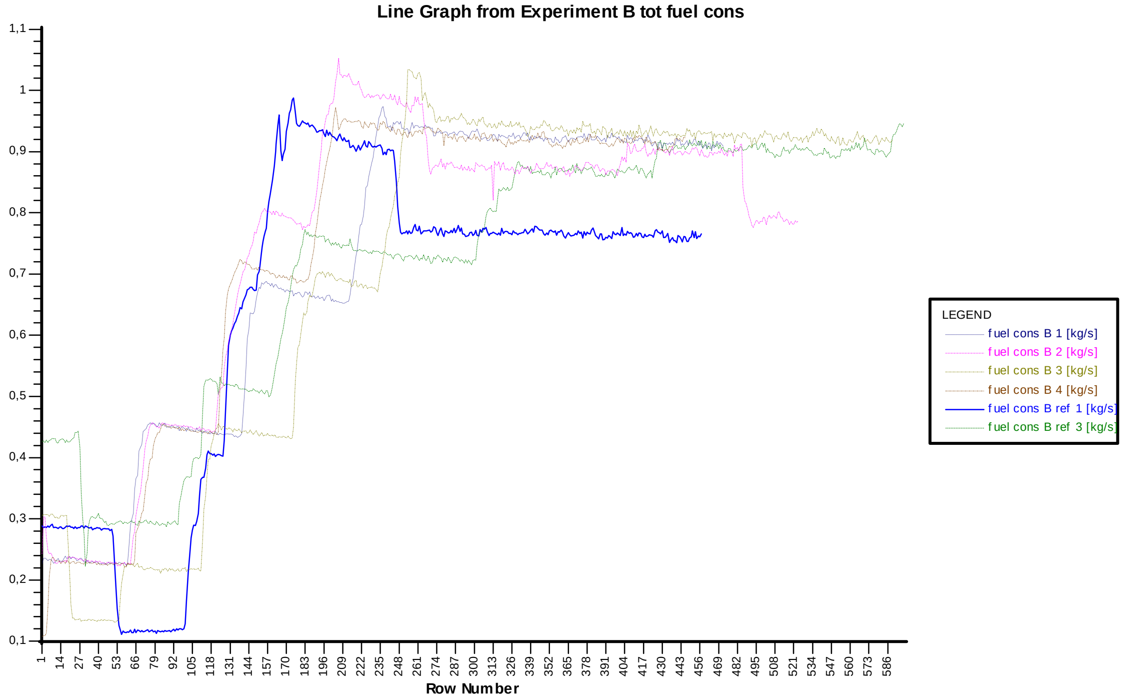


Figure 8-10 Fuel consumption in [kg/s] curves for experiment B (row number = time [2s])

8.4.2.4 Conclusions Experiment B

The comparison of the lines B ref 1 and B ref 3 shows that – during standard operation – differences in the acceleration process between different cycles can be large. This can for instance be dependent upon the officer on duty. Each officer has his own way of handling the vessel. During the described experiments six different Officers were on duty, which all use their own style and method for acceleration. It can be interesting to investigate further which Officer´s method qualifies as best-in-class.

Potential savings:
15 seconds of extra acceleration time saves 40 kg of fuel, so over 120 kg of CO_2, over 2 kg of SO_x and over 1 kg of NO_x. By just considering fuel costs this work method would save $20 dollar[c]. Speaking in financial terms this is likely to be a feasible work method but this should be calculated more specifically by the project estimation department of a dredging contractor.

In theory operational improvement during acceleration has the potential for savings. On the other hand on the 80 MT of fuel the vessel consumes during one day the reduction is marginal. The human energy required to educate vessel staff and control their performances is large. Moreover,

[c] IFO 380 price, Rotterdam, March 2008

the large difference between the reference experiments showed that the differences in Officer work methods are large; it would require big efforts to standardize the work methods. Another issue is the work pleasure of the Officers. The acceleration period is one of little phases where the officer feels his influence on the actual work. A free translation of a quote of one of the Officers is "Please do not invent measures in which we should change our own methods into a standard format." The loss of work pleasure could be a high price to pay for a limited amount of reductions. This issue will be addressed further in paragraph 11.1.2.3.

8.5 From results to design

This chapter has identified several relationships. Theoretical relations for the conversion of data output into performance indicators and empirical relations for the effect of changes in operational functions on the value of the performance indicators.

In the continuation of this research the feasibility of operational improvement will be investigated to identify the potential savings in fuel consumption and emissions and to provide recommendations for a best practice. The next chapter uses the identified relations of this chapter for the definition of a standard model which can be used for project planning and in combination with a scenario analysis can identify the feasible region for savings.

Part IV Design

9 Decision-making tool

The relations identified in chapter 8 have been translated into a spread sheet model that can function as a decision-making tool (the decision-making tool will be referred to in this report as 'the model'). In this chapter the definition, usability and verification of this spread sheet model are described.

9.1 Model construction

Microsoft Excel software is used as modelling language for the model. Excel is a well known program for spread sheet models, which makes the model easy to use. Within the company Boskalis – where the model is designed for – Excel is used for all project planning, which makes integration with the current project planning easily achievable.

The model consists of different interlinked spreadsheets. There are variable definition sheets and performance sheets. The variables in the definition sheets correspond to the different types of variables as they were identified in the system diagram (see Figure 2-3). The model consists of the following sheets:

Variable definition sheets:

- Input variables (steering and environment variables)
- Fuel specification variables (environment variables)
- System variables
- Output variables

Performance sheets:

- Cycle estimation
- Scenarios

In the variable definition sheets single values of all variables are defined. The performance sheets the use these output variables to make further calculations. The cycle estimation sheet enables the user to see the effect of changes on the complete cycle estimation, as it is drawn for the planning of a project. The scenarios sheet facilitates future planning that provides insight into which circumstances create a feasible environment for 'Vessel Speed Reduction'. The variable definition sheets will be explained in the continuation of this chapter. The performance sheets will be discussed in Chapter 10.

9.1.1.1 Sheet: Input variables

This sheet contains all input variables the user should specify. It contains both the steering variables and part of the environment variables of the system. The user of the model chooses the values of the variables and thereby inserts them in the model. If no value is defined by the user the model will insert an average value, after asking the user whether he is sure to not define a value. This sheet is open to all users and values can be varied without restrictions.

Figure 9-1 shows the user interface of the input sheet; the values of the variables need to be entered inside the black boxes. This sheet requires the definition of hopper volume and Pitch capacity (the percentage of maximum propeller angle (thus speed) that is demanded on the bridge). The environment variable blocks ask the user to define financial variables: the market prices of fuel, emission, operation time and dredged material.

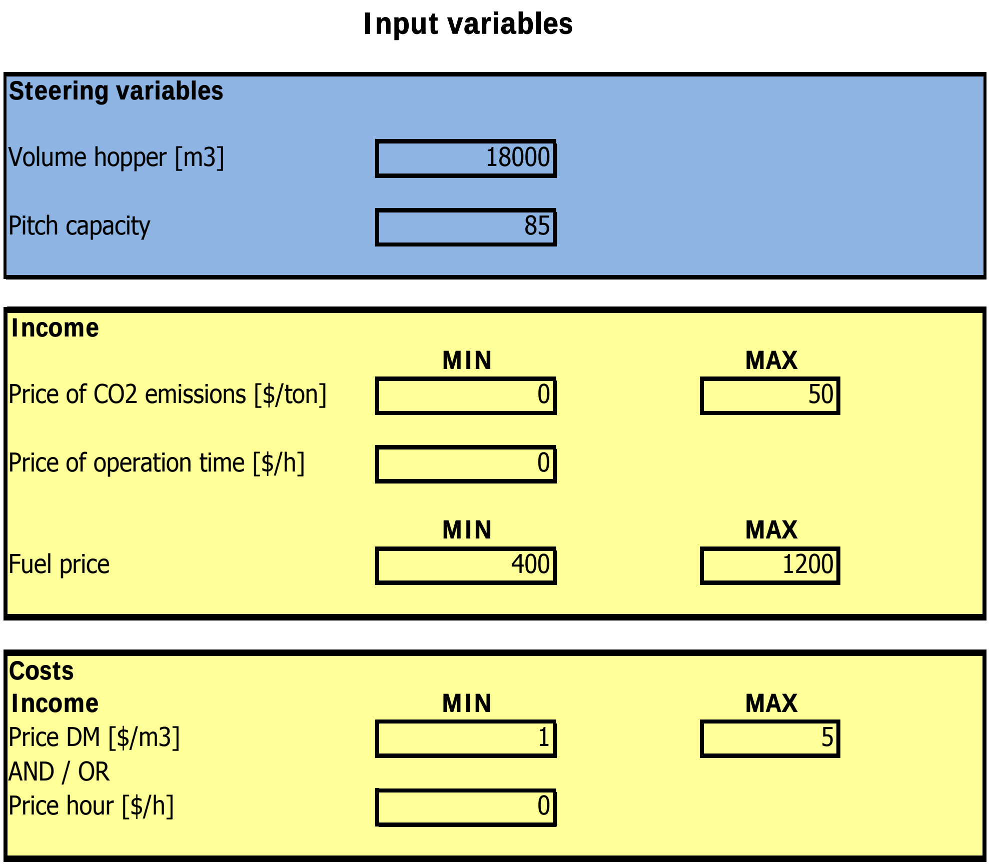


Figure 9-1 User interface of input variable sheet

The input variable sheet combines the steering variables and part of the environment variables in one sheet, so any user of the sheet can conveniently define all input using only one sheet. The environment variables, included in this sheet are the financial environment variables. These are the environment variables, likely to be influenced substantially by circumstances. The values of the financial environment variables can change significantly and it can be interesting to see what the influence of those changes is on the output values. In paragraph 10.2 scenarios will be discussed that describe the influence of changes in these environment (or so called scenario) variables on the feasibility of VSR.

9.1.1.2 Sheet: Fuel specifications

This sheet contains part of the environment variables of the system: the fuel specifications. Most values in this sheet can be specified by the user according to circumstances. E.g. if alternative fossil fuels [75] are used, or fuels with different specifications, this can be easily entered in the model. The model automatically calculates the effect of this on the emission production. If the user does not define a value, an average value will be inserted automatically. The fuel specifications sheet is open for viewing reference to all users but only experienced users are to change the values. For basic users average values are available in the model.

As described this sheet only contains the fuel specifications; they are stable environment variables. It depends on the intentions of the user whether he needs to change them. E.g. for exact cycle estimation where the user is interested in the exact emission output of the system, it is important to specify fuel specifications correctly. If the model is used for scenario analysis the main purpose is the comparison of output for different values of the scenario variables. In that case average values for the fuel specifications are sufficient.

Fuel specifications		
Fuel type		HFO 380
	C	87
mass fraction [%]	H	10
	S	3
density [kg/m3]		991

Figure 9-2 User interface fuel specifications sheet

Figure 9-2 shows the layout of the fuel specifications sheet. The fuel type can be specified, together with the fuel weight percentages and density. The fuel type is defined as environment variable in this research because the influence of operational change on the performance indicators is investigated for a given project situation. The project location usually determines what type of fuel should be used – e.g. LSFO in the North Sea (SECA-regulation). Therefore, the fuel type is not considered a steering variable. Naturally the model is suitable to investigate the effect of a change in fuel type.

9.1.1.3 Sheet: System variables

This sheet contains the steps of the system required to translate input factors in output factors. The relations, described in chapter 8 – both theoretical and empirical – are defined in this part. E.g. the input variable Pitch capacity can be specified at a certain percentage. The system variables search the corresponding power output and vessel speed for this Pitch and use these values for further calculations. The system variables sheet is only available to expert users; relations should only be changed if future research provides additional indication to do so.

9.1.1.4 Sheet: Output variables

This sheet contains the output variables or performance indicators of the system diagram, these are the factors the model user is ultimately interested in. In this sheet the user is able to see the effect in costs and emission of changing the steering and financial environment variables. The block 'revenues' should be handled carefully. The factor profit is only a representation of income per mass of dredged material minus fuel and emission costs; factors like personnel costs can be added by defining a value for 'price of operation time'. Profound information about the financial planning of a project is required for a complete insight in revenues. This financial information is not available for this research but the values can be specified in the model by project estimators to research the feasibility of VSR for a specific dredging project. In this research assumptions will be used for the financial input to provide examples of the model's capabilities. No further research will be conducted into the accurateness of used financial inputs, therefore no conclusions should be drawn on financial matters based on the output of discussed model.

Costs	[$/h]
Emissions costs CO2	0
Time costs	0
Fuel costs	1495,834
Total costs	1495,834

Revenues	[$/h]
Income	9975
Profit	8479,166

Emissions	[ton/h]	[ton/m3]
Nox	0,211552	2,12E-05
Sox	0,224375	2,25E-05
CO2	11,92927	0,001196

Figure 9-3 User interface of output variable sheet

The output sheet provides a user interface (Figure 9-3) that contains output values for performance indicators calculated from user-defined input variables. These outputs alone provide values per hour for particular circumstances. The same variables are currently available in the database of project estimators, but this model provides updated output information. The output values are used for further calculation to analyze what their effect is on the complete dredging cycle or to enable a feasibility study for optimal speed. The calculations of further performance output are defined in the two performance sheets: cycle estimation and scenario planning. These two sheets will be explained in paragraph 10.1 and paragraph 10.2.

9.2 'Performance Standard Rate' (PSR)

To enable fair comparison of performances it is desirable to express emission based on performed production. This method is used in the Dutch NO_x emission trading scheme (see paragraph 4.3.2), where quota for a region are based on the region´s production. In the emission output block the value of emission per cubic metre of dredged material is available. This unit enables the fair comparison of emission; the realization of a project might take twice as long but in total its ´global ecological footprint´ [[7]] will be reduced.

The output sheet provides values of performance indicators per hour. During project estimation the fuel consumption or production are calculated per hour. In paragraph 10.1 more will be explained about the expression of emission in 'Performance Standard Rate' (PSR).

9.3 User flexibility

Chapter 3.6 explained the need to design the decision-making tool with a sufficient level of flexibility. A model needs to be suitable for application in different parts of the company to assure that different company levels can cooperate and have insight into each other's work. This minimizes the asymmetry in information.

The spread sheet model is constructed in different sheets to assure flexible adjustment to user interest and work environment. The model is specifically designed for project planning but the content could also be useful for reference at other company departments. Each spread sheet holds remarks about the intended user and adjustability of data. Some data are exclusively available to experienced users; they will have the possibility to make adjustments after appropriate further research has been carried out to provide extra information. Other sheets are available to all users, specifically to provide insight in developments at all times to all stakeholders. In chapter 11 the different intended users will be discussed in further detail.

9.4 Verification

The verification of the model checks if the model functions correctly, so whether values are calculated in the correct way. Verification is executed to check the reliability of the model. The more robust the model is, the more it becomes possible to base conclusions on the output of the model. As verification of this model an extreme values analysis and a sensitivity analysis have been conducted.

9.4.1 Extreme values analysis

The extreme values analysis checks if the model responds correctly to extremely high or extremely low values. An example of an extreme value check is: are the fuel costs $0 if the fuel price is set to $0. The model reacts logically to extreme values. An example result of the extreme values analysis can be found in Appendix I.

9.4.2 Sensitivity analysis

The next verification test is the sensitivity analysis. This test checks the effect of small changes in input on the output variables. This test provides an indication of the sensitivity of the model to small changes in specific values, in other words robustness.

The outcomes of the sensitivity analysis indicate that the output variable:
- emission costs is sensitive to the input variable Pitch capacity
- the outcome of total costs is sensitive for the input variable emission price

Therefore, these values need to be checked; this relation will be discussed further in paragraph 10.2.4.2. The example calculation of the sensitivity analysis can be found in Appendix I.

The verification of the model shows that the model functions correctly. It responds logically to extreme values. The output is sensitive to several values but all of these can be explained.

9.5 Validation

The validation of the model serves to check whether the model indeed calculates the output it is supposed to calculate. Do the calculated numbers correspond to the actual situation? The validation has been carried out by comparing output of the model to experience numbers. E.g.

the fuel consumption per day that is measured manually on board is used to check the model output of fuel consumption.

The values of relations found with the experiments of this research are rough and based on a small number of experiment series. Once the feasible region for capacity reduction is identified the relations should be validated by performing part of the same experiments on identical or similar constructed vessels. The example calculation of the validation with experience numbers can be found in Appendix I.

9.6 From output to performance

The verification and validation of the model indicate that the model calculates values in the correct way and that these values correspond to the expected values. Therefore, the model is appropriate for use in cycle estimation and scenario analysis which will be described in chapter 10.

10 Performances

The model or decision-making tool as described in chapter 9 serves two purposes: I) Cycle estimation and II) Scenario analysis.

This chapter uses the model to investigate the feasibility of VSR for a dredging contractor, so to facilitate the decision-making on introduction of this measure.

10.1 Cycle estimation

A contractor normally presents an estimation of the complete dredging cycle to a client. In this estimation each dredging phase is calculated per minute. In the future the contractor would like to offer a client different alternatives of the estimated dredging cycle. The model of this research makes it possible to calculate the changes in the project estimation.

An example of such a project estimation is shown below for the project of Ras Laffan where the trials were held. Table 10-1 shows the cycle estimation as it is currently carried out at 100% capacity. Table 10-2 shows what would change in the cycle if - during sailing phases - vessel speed is reduced to 80% of maximum capacity.

Table 10-1 Dredging cycle estimation Ras Laffan 100% operation

Estimation Ras Laffan 100% sailing speed

Source	JV4	ALL								
Destination	DDR 4	JV 4								
Disch. Method	Pump ash. Sand	Dump Silt	D [naut.m]	v_w [kts.]	Fuel consumed [ton]	Fuel costs [$]	Emission costs [$]	Nox [ton]	Sox [ton]	CO2 [ton]
Average nett load [m3]	16000	5400								
loading sand [min]	133						0			
sailing full sand	94		20.83667	13.3	5.1258827	2819.235	0	0.331431467	0.307553	16.35157
connecting	20	5			1.0906133	599.8373	0	0.070517333	0.065437	3.479057
discharging load by pump	87				4.744168	2609.292	0	0.3067504	0.28465	15.1339
pumping water							0	0	0	0
disconnecting							0	0	0	0
sailing empty	20		2.666667	8	1.0906133	599.8373	0	0.070517333	0.065437	3.479057
dredging silt		30					0	0	0	0
sailing silt loaded		100	22.16667	13.3	5.4530667	2999.187	0	0.352586667	0.327184	17.39528
dumping		25					0	0	0	0
sailing empty sprint		15	4	16	0.81796	449.878	0	0.052888	0.049078	2.609292
Total	354	175			18.322304	10077.27	0	1.1846912	1.099338	58.44815
Estimated cycle production |	2711.8644	1851.429		Emissions	[kg/m3]			0.0740432	0.068709	3.653009
Estimated loading productio	120.30075	180		Fuel costs	[$/m3]	0.629829				
Estimated discharging produ	183.90805	216								

Table 10-2 Dredging cycle estimation Ras Laffan 80% operation

Estimation Ras Laffan 80% sailing speed

Source	JV4	ALL								
Destination	DDR 4	JV 4								
Disch. Method	Pump ash. Sand	Dump Silt	D [naut.m]	v_w [kts.]	Fuel consumed [ton]	Fuel costs [$]	Emission costs [$]	Nox [ton]	Sox [ton]	CO2 [ton]
Average nett load [m3]	16000	5400								
loading sand [min]	133						0			
sailing full sand	103.75104		20.83667	12.05	3.5360083	1944.805	0	0.228632703	0.21216	11.27987
connecting	20	5			0.6816333	374.8983	0	0.044073333	0.040898	2.17441
discharging load by pump	87				2.965105	1630.808	0	0.191719	0.177906	9.458685
pumping water							0	0	0	0
disconnecting							0	0	0	0
sailing empty	21.333333		2.666667	7.5	0.7270756	399.8916	0	0.047011556	0.043625	2.319371
dredging silt		30					0	0	0	0
sailing silt loaded		110.3734	22.16667	12.05	3.7617109	2068.941	0	0.243226279	0.225703	11.99986
dumping		25					0	0	0	0
sailing empty sprint		16	4	15	0.5453067	299.9187	0	0.035258667	0.032718	1.739528
Total	365.08437	186.3734			12.21684	6719.262	0	0.789921538	0.73301	38.97172
Estimated cycle production		2629.5292	1738.445		Emissions [kg/m3]				0.049370096	0.045813	2.435732
Estimated loading productio	120.30075	180		Fuel costs [$/m3]		0.419954				
Estimated discharging produ	183.90805	216								

The project estimation values are represented in PSR notation; performances are directly calculated for their influence per unit of production. The light blue value represents the fuel costs per cubic meter of dredged material. The red values represent the produced emission per cubic meter of dredged material.

The PSR value for emission and fuel costs (red and blue values) in Table 10-1 and Table 10-2 show that the effect of changing from 100% to 80% of maximum capacity is:

- + 3% of cycle time (365 minutes instead of 354)
- - 33% of fuel costs
- - 33% of emission

The cycle estimation sheet shows the effect of VSR on the dredging cycle. The feasibility of VSR will be different for each project situation and depends on the financial environment variables. The scenario analysis can support the contractor in identifying the feasible region under different circumstances.

10.2 Scenarios for optimization

The reference measurements and experiments on board have provided numbers about the actual influence of operational changes on fuel consumption and emission production. With these results it is possible to optimize projects and determine if and where a feasible region for 'Vessel Speed Reduction' exists.

The optimization is based on six scenarios that all know a significant change in one environment variable. The scenarios show what the effect of changes in environment variables would be on the performance indicators of the system. Figure 10-1 represents the scenario axes in an x, y, z figure; these axes represent the three scenario variables (or financial environment variables). The axes show that the different scenarios are non-exclusive; this means that it is possible for two or more scenarios to occur at the same time. The fuel price can decrease while the emission price increases.

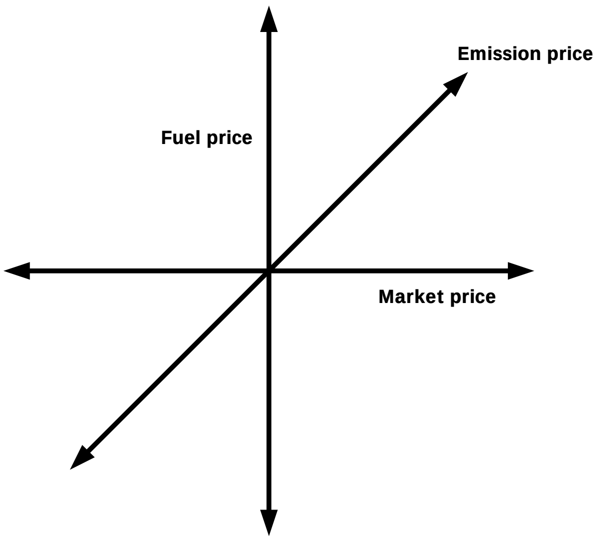


Figure 10-1 Scenario variables represented on x-y-x axes

The scenarios for the optimization experiments are summarized in Table 10-3. For each scenario the name is provided and a short explanation of the events that will occur during this scenario. The far right column indicates which environment variable is affected by each scenario.

Table 10-3 Overview of scenarios

	Scenario name	Scenario events	Scenario variable
0	Business as usual	No significant change compared with current situation	-
1	Oil price	Price of crude oil will increase	Fuel price
2	Taxing / subsidizing / trading emission	Emission of shipping will be charged in yet to be defined way	Emission price
3	Reputation client	The client will become interested in cleaner performance	Market price dredged material
4	Reputation dredging contractor	The contractor will be interested in cleaner performance	Market price dredged material
5	Dredging industry market position	The dredging industry will	Market price

	know strong or weak demand on capacity	dredged material

10.2.1 Scenario 0 Business as usual

The model shows what the current influence is on the performance indicators, for future reference it depicts the situation if everything stays the same. This scenario does not foresee any real institutionalization for the taxing of emission. Private companies will continue to have economic objectives as their main goals, the dredging market will remain steady but highly competitive, the fuel price will not rise considerably and because of the scarceness of dredging vessels it will be able to charge the client for the fuel costs.

This scenario justifies a continuation of the current work methods.

10.2.2 Scenario 1 Fuel price

Scenario 1 investigates the effect of a change in fuel prices on the feasibility of 'Vessel Speed Reduction'. Fuel prices have risen considerably over the past years and this trend is expected to continue.

Table 10-4 represents an example of part of the scenario sheet. In the upper table scenario 1 – Change in fuel prices - is represented versus vessel speed. Exact financial information about a dredging project is not available in this report. To predict the effect of scenario 1 a fictive revenue of $1 per m^3 of dredged material is used. The scenario sheet calculates when the added value of extra production is highest. In each column the hourly fuel and emission cost minus the income are displayed. The highest value indicates the optimal sailing speed; this value can be recognised because it is visualized by the largest block.

Table 10-4 Scenario 1 - fuel price between $400 and $800

Speed [kts]	Fuel [$/MT] / Pitch [%]	400	500	600	700	800
13,3	92	8.479	8.105	7.731	7.357	6.983
13,2	90	8.503	8.163	7.823	7.483	7.143
12,6	85	8.388	8.122	7.856	7.591	7.325
12,1	80	8.103	7.869	7.635	7.401	7.168
11,5	75	7.775	7.563	7.350	7.138	6.925
11,0	70	7.431	7.235	7.040	6.844	6.649

Whether a high fuel price will actually lead to VSR will largely depend on the values of the other scenario variables. If the market is to become very scarce, with large demand and a limited number of vessels, the fuel price is likely to be transferred upon clients (see scenario 5). When income is fixed (as defined in the project's contract) or when time is available (during mobilisation) the fuel price has a strong influence on the feasibility of VSR; fuel costs reduction will then have a positive influence on the hourly revenue.

10.2.3 Scenario 2 Emission price

It is likely that the production of emission (especially CO_2) will have a price in the future, but in what way they will be charged is uncertain. This scenario foresees an inclusion of shipping into an emission trading scheme for CO_2 that is now known on land. This system will put a generic price per ton CO_2 on production. This scenario can equally be used to calculate the influence of the emission price of SO_x and NO_x on the performance output.

Specific attention should be paid to which organisation is charged with the costs of emission. During mobilisation this will certainly be the dredging contractor, but during project work this could very well be the client. In this case the dredging contractor could create himself a competitive advantage by providing the client with the information generated with this decision-making-tool and provide this client with the opportunity to request different operational behaviour.

10.2.4 Combination of scenario 1 and 2

In this paragraph the effects of scenario 1 and 2 are combined. The variables fuel price and emission price have a similar effect on the hourly revenue and it is interesting to see the scenarios develop in three directions.

10.2.4.1 High fuel price low emission price

Table 10-4 showed that the outcome of hourly revenue is highly dependent upon fuel price. Table 10-5 shows the combination of scenario 1 and scenario 2. The three tables below each other indicate the effect of scenario 2; the upper table shows the scenario without a CO_2 price; the lowest table the scenario with a price of twenty-five dollar per ton. The effect of this change is that the absolute values for hourly income decrease. The distribution of the blocks becomes stronger (the difference becomes larger between different Pitch demand) but the feasible region does not significantly change for these prices. The influence of fuel price remains dominant over the emission price.

Table 10-5 Example of scenario sheet: scenario 1 and 2

0,0 [$/ton CO2]

Speed [kts]	Pitch [%] \ Fuel [$/MT]	400	500	600	700	800
13,3	92	8.479	8.105	7.731	7.357	6.983
13,2	90	8.503	8.163	7.823	7.483	7.143
12,6	85	8.388	8.122	7.856	7.591	7.325
12,1	80	8.103	7.869	7.635	7.401	7.168
11,5	75	7.775	7.563	7.350	7.138	6.925
11,0	70	7.431	7.235	7.040	6.844	6.649

25,0 [$/ton CO2]

Speed [kts]	Pitch [%] \ Fuel [$/MT]	400	500	600	700	800
13,3	92	8.218	7.844	7.470	7.096	6.722
13,2	90	8.265	7.925	7.586	7.246	6.906
12,6	85	8.202	7.937	7.671	7.406	7.140
12,1	80	7.940	7.706	7.472	7.238	7.005
11,5	75	7.627	7.414	7.202	6.989	6.777
11,0	70	7.294	7.099	6.903	6.708	6.512

50,0 [$/ton CO2]

Speed [kts]	Pitch [%] \ Fuel [$/MT]	400	500	600	700	800
13,3	92	€ 7.957	€ 7.583	€ 7.209	€ 6.835	€ 6.461
13,2	90	€ 8.028	€ 7.688	€ 7.348	€ 7.008	€ 6.668
12,6	85	€ 8.017	€ 7.751	€ 7.486	€ 7.220	€ 6.955
12,1	80	€ 7.776	€ 7.543	€ 7.309	€ 7.075	€ 6.842
11,5	75	€ 7.479	€ 7.266	€ 7.054	€ 6.841	€ 6.629
11,0	70	€ 7.158	€ 6.962	€ 6.767	€ 6.571	€ 6.376

It is important to note that when the revenue blocks in Table 10-5 are almost of the same size it does not make a financial difference if Vessel Speed is reduced – nevertheless, the emission is reduced significantly. When the result is analyzed with multi-objectives and the environmental objective is added next to the economic objective, the lower capacity option is superior to maximal capacity.

The dependence on carbon emission rights is much smaller than the dependence on fuel price for the time being. This is solely so because the price of emission rights is much lower. In March 2008 the marine fuel price is $472 per MT (IFO 380, Rotterdam [[76]]) against $33 per ton CO_2 emission in the European Union [[77]]. If shipping were to be introduced in the emission rights trading scheme or would in any other way be taxed for the CO_2 emits the influence of this price would under the current price prospects be small.

10.2.4.2 Equal fuel and emission price

The sensitivity analysis of the model showed that the hourly revenue is highly dependent on the emission price. The mass ratio between fuel and CO_2 is larger than 1:3: 1 MT of fuel causes more than 3 ton of CO_2, therefore, the effect of +/ - 10% in carbon prices is 3 times as large as + / - 10% in fuel price. This effect is visible in Table 10-6, if the fuel price increases from $0 to $12.5 and the emission price stays constant the total hourly costs increase a factor 3 in respect to when the emission price increases and the fuel price stays constant.

Table 10-6 Example of Scenario 1+2 with fuel price and emission price, both varied between 0 and 25

0,0 [$/ton CO2]

Speed [kts]	Pitch [%] \ Fuel [$/MT]	0,0	12,5	25,0
13,3	92	0	-47	-93
13,2	90	0	-42	-85
12,6	85	0	-33	-66
12,1	80	0	-29	-58
11,5	75	0	-27	-53
11,0	70	0	-24	-49

12,5 [$/ton CO2]

Speed [kts]	Pitch [%] \ Fuel [$/MT]	0,0	12,5	25,0
13,3	92	-130	-177	-224
13,2	90	-119	-161	-204
12,6	85	-93	-126	-159
12,1	80	-82	-111	-140
11,5	75	-74	-101	-127
11,0	70	-68	-93	-117

25,0 [$/ton CO2]

Speed [kts]	Pitch [%] \ Fuel [$/MT]	0,0	12,5	25,0
13,3	92	-261	-308	-354
13,2	90	-237	-280	-322
12,6	85	-185	-219	-252
12,1	80	-163	-192	-222
11,5	75	-148	-175	-201
11,0	70	-136	-161	-185

Whether market based or not, through emission rights or tax; the emission price will always lay in governmental control. Governments are the final decision-makers about the emission quota. The interest of the government in the economy makes it unlikely that they will let the price of emission come so close to the fuel price that the influence of emission costs becomes dominant. Emission costs will possibly make a difference when rounding off between higher or lower capacity, but will never be responsible for a radical change in work method or culture.

10.2.5 Scenario 3 Large environmental awareness from client

Scenario 3 focuses on the client becoming more and more interested in low-emission performance and the effect this can have on their reputation. This means that the client will be willing to pay an extra fee for cleaner operation. This is highly dependent on preferences of the client; a client with time as it first priority will be interested in the 100% method. A client like for instance the Rotterdam port authority in the case of Maasvlakte II is possibly interested in a cleaner construction method [78].

To make operation feasible the client should pay the difference in income between maximum and reduced capacity. It is difficult to quantify a realistic fee of what the client might be willing to pay for this. Project planning of a contractor should calculate which price is reasonable.

Because the reputation of the client is a difficult variable for quantification the 'Performance Standard Rate' is essential. By using 'Performance Standard Rate' (PSR) the amount of emission a vessel is allowed to produce will be based on its production. For this scenario it is important to express emission related to amount of production. If emission is expressed in gram per cubic metre of produced dredged material it is possible for the client to see what the impact of their project is on the environment.

10.2.6 Scenario 4 Large environmental awareness from contractor

In this scenario the contractor becomes more and more aware of its environmental performances and is possibly subject of large public pressure to reduce it. This scenario resembles scenario 3. Emission should be expressed in gram per cubic metre or during mobilisation in gram per mile.

10.2.7 Scenario 5 Strong or weak market demand

The development of the dredging market will strongly influence the feasibility of VSR. The development of the market is often criticized for being unilateral and depending on a limited number of large clients. On the other hand the current societal developments foresee that, in particular climate change will be responsible for a large growth in the dredging sector. The market demand has a strong influence on feasibility of emission reduction. When dredging vessels are scarce and the demand is high, contractors will be able to increase their prices of dredged material and it will be attractive to produce as fast as possible. On a market with many vessels and little demand for projects will decrease the market price of dredged material. Producing as cheap as possible will become important and VSR can decrease fuel costs in this situation.

The effect of change in scenario 5 is indicated by putting a higher price on a cubic metre of dredged material. Table 10-7 shows the effect of a change in dredged material revenue combined with scenario 1 (fuel price) on the hourly income. If the price shifts from $1 to $2 per cubic metre of dredged material the feasible region for VSR changes considerably. The blocks of the upper table show that the optimal speed shifts for different fuel prices. The lower table indicates that at a price of $2 per m^3 – as long as the fuel price remains below 800 [$/MT] – maximum speed is always the most lucrative option.

Table 10-7 Example of scenario sheet price dredged material and fuel price

1,0 [$/m3 DM]

Speed [kts]	Fuel [$/MT] / Pitch [%]	400	500	600	700	800
13,3	92	8.479	8.105	7.731	7.357	6.983
13,2	90	8.503	8.163	7.823	7.483	7.143
12,6	85	8.388	8.122	7.856	7.591	7.325
12,1	80	8.103	7.869	7.635	7.401	7.168
11,5	75	7.775	7.563	7.350	7.138	6.925
11,0	70	7.431	7.235	7.040	6.844	6.649

2,0 [$/m3 DM]

Speed [kts]	Fuel [$/MT] / Pitch [%]	400	500	600	700	800
13,3	92	18.454	18.080	17.706	17.332	16.958
13,2	90	18.365	18.025	17.685	17.345	17.005
12,6	85	17.838	17.572	17.306	17.041	16.775
12,1	80	17.140	16.906	16.673	16.439	16.205
11,5	75	16.400	16.188	15.975	15.763	15.550
11,0	70	15.643	15.448	15.252	15.057	14.861

11 Process design

This chapter relates back to the process perspective as described in chapter 3. It provides a process design which describes the required steps for an implementation of change. In chapter 3 three different relationships between stakeholders were analyzed:

1) The relation between stakeholders within the contractor agency (problem owner), between head office, project office and vessel (possibly of subcontractor) staff.
2) The relation between contractor and outside world.
3) The relation between contractor and authorities.

All three of these relationships are essential and this chapter discusses the interfaces between stakeholders in them. However, the main focus of this process design is on the internal relationships with the problem owner (the dredging contractor). ISO 14001 or any Environmental Management system [[79]] shows that integration of environmental measures within the entire company is essential. Moreover, measures can only be successful if the empowered stakeholder (the vessel staff) realizes them.

In chapter 3, a range of principal-agent problems that occur within this relation were identified. Therefore, in this chapter specific attention is given to how to solve these principal agent problems and assure successful implementation of the model.

11.1 Process change within organisation

This paragraph provides recommendations on how to achieve company-wide process change and in particular how to deal with the principal-agent problems between head office and vessel staff.

11.1.1 From maximal production to minimal emission

As described in paragraph 3.3, vessel staff – together with the rest of a dredging organisation – is purely focused on maximizing production and finishing each dredging phase as fast as possible. In order to introduce a new performance indicator aimed at the minimization of emission per production unit the mindset of company employees needs to undergo a transformation. A transition of mindset and working method is never easy to realize. Moreover, the dredging industry is conservative; vessel staff is proud of their work and highly self-aware during operation. At the same time the relation between head office and vessel staff has been identified as a typical principal agent relation which complicates controlling of the actions of vessel staff.

During the trial period strong attention has been paid to the requirements such a transition – from maximal production to minimal emission – would entail. Conversations with staff and monitoring of their work methods on board, received large attention. Also on other events[d] visited for this research – where environmental measures in shipping were discussed – the reactions of vessel staff were analyzed closely. Valuable information was gathered from discussion with Maritime Officer students. To gather as much independent and sincere – rather than socially desirable – reactions as possible the position of a friend and fellow student, rather than an environmental specialist, was adopted at these occasions.

[d] Pro Sea Maritime Environmental Awareness course (September 2007); Seminars Platform ship emissions September and November 2007)

During the research period several brainstorming sessions were held where the participants were asked to think of mechanisms to motivate staff, to adapt their work method. Next to a lot of sceptical reactions, this research method also generated a number of interesting propositions. The next paragraphs will highlight the most promising propositions based on the principal-agent problems they could be able to solve.

11.1.2 Principal-agent problems

In paragraph 3.3.1 three typical agency theory problems were described: I) Asymmetry of information II) Hidden characteristics and III) Hidden action. These problems create a situation in which it is difficult for a contractor's head office to integrate change on board. Vessel staff needs to be motivated appropriately to adjust their work method.

"Agency theory focuses on 'incentives' and 'monitoring' as two possible solutions to agency problems [[80]]."These two categories are described in this chapter and specific solutions are proposed for this problem within a dredging contractor. Finally, this research adds a third category, namely the aspect of creating commitment by good communication.

11.1.2.1 Incentives

'Incentives' are the most straight forward solution to principal-agent problems; an agent is stimulated to perform actions, because a reward is promised to him / her upon correct execution. 'Incentives' are particularly suitable to control hidden action on board. Officers will be motivated to prove their correct performances because they are interested in the accompanying award.

Below several possibilities for incentive methods are listed. These are specific examples of options that could motivate vessel staff to change their actions. The most straight forward incentive mechanisms are:

- Motivate staff by means of their salary
- Motivate staff with rewards in kind
    - Design a system for compensation based on performances of minimal emission per production unit.
- Motivate staff with lighter workload

In addition to these straight forward mechanisms, studies of the methods of companies that have already integrated 'Vessel Speed Reduction' learned that creating minimal emission into a type of sport's goal is used as incentive mechanism [[Fout! Bladwijzer niet gedefinieerd.]] [[34]]. A few examples of this are:

- Vessel of the year contest
    - Contest where the vessel within a fleet with the best emission per production unit performances is assigned and rewarded for the staff's efforts.
- Competitions for optimal sailing
    - Compare identical or similar vessels on their performances in competitions
- Officer of the month contest
    - Compare the performances of individual Officers and assign a best practice in acceleration

The incentives that create a sport are interesting possibilities but there is a risk that mechanisms can possibly be seen as rather childish. The incentives can be used as support mechanism but a complete change in mindset should not be expected of them.

11.1.2.2 Monitoring

'Monitoring' decreases the asymmetry of information by installing mechanisms that will enlarge the principal's knowledge over on board operation. This solution is a traditional reaction of a principal that has limited accurate knowledge of operations, he is determined to find out as much as possible and limits the agent's options for decision-making.

Propositions for monitoring solutions:

- Black box system
    - Next to the recent introduction of a compulsory Voyage Data Recording (VDR [[81]]) system which registers the vessels main activities and saves them for 24 hours. A black box system for shipping could be introduced that makes it possible to trace back all actions on board.
- Increase shore-control
    - Some companies have all important decisions taken on shore in a control room. Vessel staff needs to fulfil basic or emergency actions.
- Adjust meters too low
    - In cars there is always a deviation between meter and reality to protect the automobile driver from speeding. Officers mentioned themselves that this would be the only way to control their actions.

The category monitoring contains large risks, particularly in the dredging industry. Dredging is a highly dynamic process that continuously requires decision-making. When asking employees about the specific advantages of the work the large autonomy of Officers and the constant challenge available in the optimization of production is almost always mentioned. These characteristics make dredging more difficult to monitor from shore than other shipping activities. Also the decreasing of the responsibilities of Officers creates a risk in the destruction of the work pleasure that attracts employees to the industry.

11.1.2.3 Creating commitment through communication

The three traditional categories to assure successful process change and overcome the principal-agent problems, provide mechanisms for vessel staff motivation. Not one of them is guaranteed to be successful or without risk, though. Dredging Officers are intelligent and self-aware; and are not easily convinced to change their long known standards and ways of work. At the same time they are cunning enough to get round any monitoring system that might apply. Therefore, this research proposes a fourth category, which aims at creating double-sided commitment between principal and agent through the facilitation of communication.

Creating commitment with vessel staff runs deeper than all agency problems. It focuses on the reason for the existence of the principal-agent relation; namely the difference in objectives between head office and vessel staff. By attacking this difference and motivating the staff to integrate the 'Performance Standard Rate' of emission into their objectives operational improvement will be integrated on board. Communication assures that shore departments are aware of the decisions made on board and that vessel staff understands the rationale for orders without feeling restricted in their autonomy.

The following mechanisms are proposed for communication between head office and vessel staff on the decision making process:

- Process rounds
- Provide training and support
- Expansion of decision-making tool

Process rounds
By constructing the decision-making process in process rounds [82] the vessel staff can be invited to participate in the process. The Officers can explain the head office about the operation methods now used on board and ventilate ideas on how they would initiate operational change to be implemented. Moreover, they can provide detailed information on how their motivation is stimulated best.

Provide training and support
Identification of best practices in acceleration process can be done by analysts but Officers need to be able to communicate with each other. For this a specialist can come on board to explain the best practice. This can especially provide added value, if performed between different vessels. All Officers are confident about their work method and usually do not talk with others about it. By organising training and support Officers can identify and learn best practices.

A good example for this could be the acceleration process. This research learns that there are potential savings in more controlled acceleration. The enforcement of a standard acceleration process should be handled with care though. The most important reason for this is that, this could decrease the work pleasure of Officers since acceleration is experienced as a fun activity.

During training events Officers can talk to each other and exchange experiences. The acceleration trade-off can be shown to Officers with the advice that a more controlled acceleration process can be lucrative. In this way the Officers could be motivated to change their actions and possibly even compete with each other based on new performance indicators.

The difficulty lies in the fact that training events are not always experienced as useful and interesting, and that the adsorbed information can be quickly forgotten once the trainer leaves the vessel or the Officer leaves the training room.

To support this communication direct available decision-making support is essential. The decision-making tool should be expanded to provide real-time results. If the Officer receives direct information about the system performances during acceleration, he then can choose to adapt his actions and this will in turn increase his feeling of being in control.

Decision-making support for communication and visualization
The model of this research functions as a decision-making tool for project estimation, to make feasibility trade-offs for operational functions. The principal-agent relation shows that more is required to create on board commitment to the advised actions. The model from this research has been made suitable for different levels within the organisation through protected and non-protected sheets, but it would be most effective would to install a model with direct available results connected with the technology on the vessel.

A large discussion went on at a seminar[e] whether the vessel staff should be involved in the calculations and think steps of an on board decision making tool. The proposition of scientists was that there was no purpose for Officers to be tired with several parts of an onboard real-time speed optimization tool. This statement was received badly by the attending Officers, they experienced this as an underestimation of their intellect.

[e] Seminar 'Beheersing' of Platform 'Scheepsemissies' November 2007

The following mechanisms can be used to expand this decision-making tool:

- Participation in the MARIN (Maritime Research Institute Netherlands) program for continuous on board optimization of vessel speed program
- There are dredging vessels equipped with a system that shows a smiley on screen if dredging is going 'well'; the smiley cries when things are not going well.
- Internet connection on board could be useful for better communication
    - More information will be available on shore.
    - Officers will be able to expand their knowledge about outside developments. Weather predictions and routing issues can be investigated thoroughly on board.

11.1.3 Visibility within company

Next to the good relation between head office and vessel staff it is important that the measures are integrated throughout the company; the rest of the company needs to know what measures were taken and for what reason. All departments of the company are currently convinced that maximal production is always the optimal method to reach the company objectives. By internal communication such as conferences, presentations by Officers or writing items in the company magazine employees will become acquainted with the improved operations methods. This report and presentation of this research provide a first step for this.

The next two paragraphs address briefly the relations between contractor versus external stakeholders and contractor versus authorities. The description shows how these relations can equally benefit from solid communication.

11.2 Outside world

Next to the integration inside the contractor agency it is important to maintain a good relationship between contractor and external stakeholders. Therefore, it is important that measures taken are visible to the outside world. This builds further on the visibility within the company. One of the basic requirements for visibility is communication; employees that tell external stakeholders about the actions of their company can be crucial.

For clients it is essential to see what is going on. Not only to see if their interest is being looked after correctly – whether their interest is low emission or fast production. Equally so, the client needs to be informed correctly about on board actions. If 'Vessel Speed Reduction' is implemented, a client will easily have the impression that this method will go against her interests of fast production. By including the client from the tender process onwards in the decision-making she becomes aware of the made choices and rationale[f].

11.3 Institutional perspective

Lobbying with authorities for acknowledgment of measures is essential. The abatement of emission in 'Performance Standard Rate' is a cost-effective way of supporting the environment, but is easily overlooked in the field of technical artefacts that possibly cause a more obvious

[f] A research is being executed by a communication student within the company Boskalis at this moment about the effect of a dredging project on public opinion. The results of this student´s thesis can possibly be used to realize visibility to the outside world.

reduction in one or several emission types. Nevertheless, on economical and social feasibility, and thus on sustainability, these artefacts will certainly rate less positive.

For this perspective again communication is an essential solution mechanism. Authorities need to be aware of what is going on and what the effect is of measures taken. Secondly, the contractor needs to be able to prove the environmental effect of its actions. If emission rights are introduced for CO_2 or SO_x they will most likely be charged at the acquisition of fuel so the benefit from more efficient production will easily pay itself back. For Kn_{ox} abatement on the other hand a vessel owner will need to be able to prove its efficient operation, which will require documentation of the power output of the vessel. Again a continuous process-optimization tool as described in 11.1.2.3 can be helpful in this situation.

Part V Evaluation

12 Conclusions and recommendations

In this chapter the research question is answered and suggestions for further research are described.

12.1 Conclusions

How can the emission of gases (CO_2, SO_x, NO and PM) be reduced by operational improvement in a technically, socially and economically feasible way?
Technically the reduction of emission is possible by operating below maximal Pitch capacity which reduces the 'Performance Standard Rate' of emission. The social feasibility of this method is assured by maintaining large autonomy for the vessel staff and offering them participation in the decision-making process. Economic feasibility is assured by monitoring developments in the environment variables 'fuel price', 'emission price (or tax)' and 'market demand' to calculate the optimal operation capacity for each dredging project situation.

The answers for the research sub-questions are discussed in the following paragraphs:

12.1.1 Sub-question 1

What amount of gaseous emission does the fleet produce?
The total amount of emission that a dredging vessel produces varies for each dredging phase. This research has provided a spread sheet model which calculates the emission production per hour during the different dredging phases. The layout of the dredging cycle is highly dependent on project characteristics. To enable comparison of total system performances on the emission of a vessel the emission should be expressed relative to the production (this is called 'Performance Standard Rate'). The spread-sheet model facilitates the calculation of the emission performance – of the complete dredging cycle – expressed in PSR [g/m^3 DM].

12.1.2 Sub-question 2

What are the consequences of emission of the fleet?
At this moment there are no consequences of the emission that affect the key-objectives of a dredging contractor. A few regulations on emission exist that the company has to comply with. However, currently no institutions exist that directly affect the operations management of the contractor.

The institutional environment is likely to change in the near future, an emission trading scheme could be introduced, but at this time other regulation is more likely. Technical abatement methods that require the contractor to switch to different fuels or to retrofit their engines or complete vessels are being considered by the IMO.

Introduction of such regulation on technical artefacts will cause large investment or fuel costs for the contractor. Operational improvement can equally be used as an abatement method to reduce the amount of emission. A better balanced operations management through measures like 'Vessel Speed Reduction' can reduce the Performance Standard Rate of emission for a dredging project.

However, authorities do not yet acknowledge such 'soft' mechanisms. Profound lobbying by the industry for the acknowledgement of Performance Standard Emission Rate is required to make these efforts valid as emission reduction results.

12.1.3 Sub-question 3

What factors can be identified to influence the amount of emission?

The factor identified to influence the amount of emission is the requested percentage of total Pitch capacity. The requested Pitch determines the angle of the propeller blades and in this way controls the speed of the vessel and the amount of power the engines have to deliver to bring and keep the propeller blades at this angle. The NO_x emission is directly related to the delivered power of the engine as is the fuel consumption of the engine. The emissions CO_2 and SO_x are directly related to the amount and type of fuel consumed.

12.1.4 Sub-question 4

How can operational improvement influence the factors to change the amount of emission?

The field experiments carried out for this research have investigated three possibilities on how operational improvement can lead to lower emission. A model has been constructed to support decision-making on the economic feasibility of these possibilities.

12.1.4.1 Conclusions feasibility 'Vessel Speed Reduction'

The feasibility of sailing at reduced capacity can be determined by using the cycle estimation sheet of the model. The cycle estimation shows for a specific project how much fuel and emission is saved in 'Performance Standard Rate' by reducing capacity during the sailing phases. The cycle estimation of the trial project showed that by reducing operation from 100% to 80% of maximum capacity during sailing phases a considerable reduction in fuel costs and emission can be realized against a very small time loss.

Scenario planning is available in the model to investigate at what values of the financial environment variables 'Vessel Speed Reduction' is an economically feasible option. The user can create his own scenario by combining 'fuel price, emission price and dredged material price'. The model calculates the hourly income for this scenario and provides visualization of the comparison of hourly income per Pitch capacity values.

A user – interested purely in economic feasibility – should always select the Pitch capacity that provides the highest value of hourly income for a specific scenario. However, when two options lay close together a multi-objective user – interested in environmental performance – should select the lower capacity option because this option causes less emission.

12.1.4.2 Conclusions shutting one engine down during mobilisation

During mobilisation without time pressure the tactic of using one engine at 100% of available capacity and shutting down the second is sometimes applied, by means of saving fuel. The internal efficiency of the engine increases at higher capacity which makes this option more economical than using two engines at 50%. However, the results of 'Experiment A' of this research showed that fuel consumption and thus emission is even lower when two engines run at 60%. Two engines at 60% consume less fuel and create more vessel speed than one at 100%.

12.1.4.3 Conclusions acceleration

'Experiment B and C' showed that a better controlled acceleration process could reduce the amount of emission, while causing only a small amount of time loss. Although, reductions can be achieved through this method they will be marginal. The experiments showed that the difference in fuel consumption between the fastest and slowest acceleration method is approximately 0.05% of the average daily fuel consumption. Even with 20 acceleration phases per day this will only provide a reduction of 1% in emission.

The process perspective also showed that there exists a large difference in the operation methods of different Officers. To identify a best practice and train all Officers to adopt this standard would require large effort. Installing an auto-pilot mechanism or an intelligent engine are options to standardize the process without human intervention. Machine standardization should be handled with care though, acceleration is an important activity for the work appreciation of Officers; in this phase he possesses large autonomy. Taking this out of Officer hands will most likely not be appreciated. It should be considered well if the small amount of possible reduction is worth the effort to standardize the acceleration work process.

12.1.5 Sub-question 5

What types of organisational changes are required within a dredging company to implement operational measures, aimed at reducing the amount of emission?

The transition in work methods, in particular of 'Vessel Speed Reduction' and 'controlled acceleration' will not be easy to realize. Currently the mindset of the complete company is aimed at maximal production rather than minimal emission. The process perspective of this research showed that there exists a principal-agent relation between head office and vessel staff. This relation causes the agency problems: asymmetry in information, hidden characteristics and hidden actions.

To solve these problems and to assure that the vessel staff carries out operational measures designed by the head office the classic categories of agency solutions 'incentives' and 'monitoring' have been described with examples for the dredging industry. 'Incentives' can motivate staff but because of their large level of autonomy on board it is not difficult for them to get round these obligations and as soon as an observer will leave the vessel, the staff can switch back to old methods.

'Monitoring' can increase the knowledge and control of the head office over the actions of Officers. This category contains high risks, though. Dredging is appreciated by Officers because of the high level of autonomy and decision making that is required. Installing a 'monitoring' system will certainly not improve the social acceptability of the measures and will motivate staff even more to mislead the head office.

To go further than trying to fight the agency problems, the company should attack the reason for the existence of the principal-agent relation: the difference in objectives between head office and vessel staff. If the vessel staff becomes aware of the rationale for implementation of measures they will see the effect it can have on the company's performances and thus their own salary or job assurance. The realization of this two-sided commitment should go through solid communication; from vessel staff to head office but also vice versa.

The decision-making tool should be expanded to help establish this communication. By visualizing on board, the direct effect of an Officer's actions on the output variables of 'fuel consumption', 'emission' and 'costs', he can be motivated to improve his operations to minimize these three variables.

Finally, next to the implementation on board it is essential to integrate the transition of mindset into the complete company. To create this corporate awareness, internal communication in conferences, training and media is required.

12.2 Suggestions for further research

To expand the knowledge and effectiveness of this research in this paragraph's suggestions for further research are described.

12.2.1 Financial investigation

This research has provided a decision-making tool that enables the user to investigate economic feasibility of capacity reduction measures. The optimal speed will be different for each project situation and combination of scenario variables. To make ultimate economic feasibility trade-offs further financial information is required. This is to be performed internally by the project estimation department of the dredging contractor.

12.2.2 Accuracy of experiments

When the feasible region for capacity reduction is identified, a project estimation for the optimal operation method can be developed. This estimation provides a standard layout of the dredging vessel with average values. If the estimation requires more detailed values more accurate research needs to be carried out.

As described several times in this report the accuracy of the performed experiments is low. The main objective was to research a broad range of possibilities and to identify the feasible region; therefore the experiments were designed with large variation steps. The difference between 'experiment A1 and A2' shows that the results of these experiments cannot be used for exact vessel speed planning. This requires further research: more series of experiments and more accurate technology for speed determination and fuel consumption measurement. Follow-up series of the reference measurements have already been started by the company.

12.2.3 Experiments in different dredging phases

If the economic feasibility study within the company delivers positive results for capacity reduction within the sailing phases the experiments could be expanded. 'Experiment D and E' could be performed to investigate the possibilities within the phases dredging and discharging. This research has provided setup for these experiments but they still need to be planned carefully, because they directly influence the production of material. These experiments do not need to be performed as rough as the first experiments because the results of this research provide an indication for a feasible region already. This will limit the amount of production loss during the experiments.

12.2.4 How to transfer to different vessels?

This research contained experiments at one vessel. The values found with the experiments of this research can be validated by performing the same experiments on identical or similar constructed vessels. The engine and hull specifications determine 'fuel consumption versus speed relation' of an individual vessel. Before the results can be used for other vessels or the complete fleet the relation values in the model need to be validated on different vessels. The relations between factors integrated in the model will stay the same but the values will need to be investigated separately for each type of vessel.

12.2.5 Expansion of decision-making tool

The decision-making tool of this research is designed for project estimation and is made flexible so other company departments (on shore and on board) can use it for information. The process design specifies the desirability for an on board decision-making tool that provides the Officers with direct insight into the effect of their actions.

The accuracy of the identified relations in this research is not high enough to provide real-time decision support on board. This could be the next step in the process. To achieve this more accurate and direct insight a dredging contractor can continue the research internally but can also join forces with research institutes to develop a software tool or integrated bridge system that calculates effects of changes in steering variables directly and provides continuous decision-making support for best practice in operational behaviour.

12.2.6 Mono- or multi-objective

The choice to define the objective function as a mono-objective function was deliberate. The dredging industry's key-objective is currently economic feasibility; measures are purely judged on their economic value. Therefore all are standardized in the equal costs unit. For a dredging contractor it is always essential to know which combination of factors provides the most lucrative financial balance.

The risk of a mono-objective function is that one factor overtakes all attention. One sub-objective can become so large that other factors become insignificant to the sum of sub-objectives. In such a situation the other sub-objectives can become lost from sight. If two combinations of sub-objectives are equal it is impossible to see which combination leads to the most desirable values of sub-objectives.

The objective tree of Figure 1-1 shows that the dredging contractor also has the objective to maintain a good reputation. This good reputation can be realized through a minimization of emission. The key-objective of the contractor is always economical feasibility but if two options score evenly the contractor should choose the option with minimal value of emission production.

Suggestions for further research are to use multi-objective linear programming or goal programming that split the three cost factors fuel costs, operation costs and emission costs. Such a program will compare alternatives on all three factors separately and select the method with the best combination of alternatives.

Appendix

Appendix A

List of abbreviations

CO_2	Carbon dioxide
DM	Dredged material
EU	European Union
GHG	Green house gas
HFO	Heavy fuel oil
IMO	International Maritime Organisation
ISO	International Standardisation Organisation
LSFO	Low Sulphur fuel oil
MARIN	Maritime Research Institute Netherlands
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	Marine diesel oil
MGO	Marine gas oil
NGO	Non-governmental organisation
NO_x	Nitrogen oxides
PM	Particulate Matter
PSR	Performance standard rate
SCADA	Supervisory Control and Data Acquisition
SECA	Sulphur Emission Controlled Area
SEPAM	Systems Engineering, Policy Analysis and Management
SO_x	Sulphur oxides
TU Delft	Delft University of Technology
VDR	Voyage Data Recording
VOC	Volatile Organic Compound
VSR	Vessel Speed Reduction

Appendix B

Units

Most of the units in this report are SI-units (international system of units). The shipping sector often uses different units; some of them are included in this report. The symbol used for these units by the 'International Bureau of Weights and Measures' and the conversion of the non-SI units to SI-units are defined in this section.

Distance
1 Nautical mile [M] is 1852 meters [m]

Volume
1 Measurement ton [MT] is 1.13267386368 cubic meters [m3]

Speed
1 knot [kn] = 1.852 [km/h] or approximately 0.5144444 [m/s]

Appendix C

List of figures

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Appendix E

Emission theory

This appendix contains the explanation of the calculation of the emission ratio for CO_2 and SO_x from the combustion of fossil fuel in source: Stapersma, D. (2005) Diesel Engines IV: Combustion and emission, reader course WB4408B, TU Delft

"Calculation of emission ratio
Derivation of mass ratio for CO_2 and SO_x from carbon, respectively sulphur balance.

Carbon dioxide CO_2:

The amount of carbon dioxide will be calculated from the *carbon balance.* Remember the reaction for complete combustion:

$$n_c * C + n_c * O_2 \rightarrow n_c * CO_2$$

From this it is clear that the amount of kmol carbon dioxide in the exhaust gas is equal to the number of kmol of carbon in the fuel:

$$n_{CO2} = n_c = m_c/M_c = x_c/M_c * m_f$$

Note that this is only true if the amount of CO, HC and C (all results of incomplete combustion) is neglected.

Now the kmol ratio of carbon dioxide can be obtained:

$$nr_{CO2} = x_c/M_C$$

and the mass ratio in kg / kg fuel for CO_2 is:

$$\boldsymbol{mr_{CO2} = M_{CO2}/M_C * x_C}$$

Sulphur dioxide (SO_2)

The same derivation is done for Sulphur dioxide:

Reaction for complete combustion:

$$n_S * S + n_S * O_2 \rightarrow n_S * SO_2$$

The kmol of Sulphur dioxide in the exhaust gas is equal to the number of kmol Sulphur in the fuel:

$$n_{SO2} = n_S = M_S/M_S = X_{PS}/M_S * m_f$$

Note that this is only true if no SO_3 is formed.

Kmol / kg ratio of Sulphur dioxide:

$nr_{SO2} = x_S/M_S$

Mass ratio in kg / kg fuel for SO_2 is:

$mr_{SO2} = M_{SO2}/M_S * x_S$

"Intrinsic emission:
CO_2 formation and levels for 96% C-content 3200 g / kg fuel is emitted.
Approximately 3200 g / kg fuel, dependent on fuel composition

SO_x formation and levels
Approximately 20 g / kg fuel per %S in fuel
Part of SO_2 is converted (slowly) to SO_3; normally 95% SO_2 and 5% SO_3 (SO_x)"

Appendix F

Engine shop trials

The engine shop trials carried out by the engine manufacture 'Wartsila' in 1997 determined the specific fuel consumption of the engine and the NO_x emission per kWh. The corresponding passages from the engine shop report are shown in this appendix.

NO_x rate first experiment:

13 (13)

WÄRTSILÄ NSD

CORPORATION

Emission Report

1. Background

NOx emission measurements were carried out at engine number 9974 for Verolme Heusden NB 1030 26.6.1997 at Wärtsilä NSD Finland Oy , Turku .

Engine type: Wärtsilä 12V46C MCR 12600 kW at 500 rpm

The aim of the measurement was to confirm that NOx emissions are according to the proposed IMO /MEPC requirements.

2. Test conditions

- ISO 8178 test procedure
- Nominal speed 500 rpm, constant speed
- Diesel oil operation
- ISO 8178 test cycle no. E2 (constant speed)

3. E2 Test cycle (ISO 8178)

	Testpoints:			
Speed /%:	100	100	100	100
Power/%:	100	75	50	25
Weighting factor:	0.2	0.5	0.15	0.15

4. Testresults

E2 Test cycle :

NO_x **12,01 g/kWh**

5. Conclusions:

The IMO/MEPC proposed NOx-limit is 13 g/kWh for engine with nominal speed of 500 rpm.

Measured values meet the proposed limit.

Test witnessed by

HENRI TUOMINEN

BUREAU VERITAS Surveyor at Turku PARIS 1828 International Register

27.6.1997

Wärtsilä NSD Corporation
Diesel Technology Turku
Vesa Hilakari

NO_x rate second experiment:

14 (14)

WÄRTSILÄ NSD

Emission Report

1. Background

NOx emission measurements were carried out at engine number 9975 for Verolme Heusden NB 1030 10.7.1997 at Wärtsilä NSD Finland Oy , Turku .

Engine type: Wärtsilä 12V46C MCR 12600 kW at 500 rpm

The aim of the measurement was to confirm that NOx emissions are according to the proposed IMO /MEPC requirements.

2. Test conditions

- ISO 8178 test procedure
- Nominal speed 500 rpm, constant speed
- Diesel oil operation
- ISO 8178 test cycle no. E2 (constant speed)

3. E2 Test cycle (ISO 8178)

	Testpoints:			
Speed /%:	100	100	100	100
Power/%:	100	75	50	25
Weighting factor:	0,2	0,5	0,15	0,15

4. Testresults

E2 Test cycle :

NO_x **12,03 g/kWh**

5. Conclusions:

The IMO/MEPC proposed NOx-limit is 13 g/kWh for engine with nominal speed of 500 rpm.

Measured values meet the proposed limit.

HENRI TUOMINEN

BUREAU VERITAS
Surveyor at Turku
PARIS 1828
International Register

Wärtsilä NSD Corporation
Diesel Technology Turku
Arto Sarvi

10.7.1997

Determination of specific fuel consumption for MDO and HFO 380:

13 (14)

WÄRTSILÄ DIESEL

SPECIFIC FUEL CONSUMPTION

DATE 10.07.1997

Engine type	WÅRTSILÄ 12V46C
Engine number	9975
Nominal power	12600 kW
Nominal speed	500 1/MIN
Installation	VEROLME
Measured by	T.SALMINEN
Note	

ISO 3046/1 conditions

– inlet air temperature	T1	25
– C.A.cool.water temp LT	T2	25
temp HT	T3	75
– barom. pressure mmHg	P1	750

Reference value kJ 42700

Fuel			
	MARINE DIESEL FUEL MDF	– calorific value kJ/kg	42600
		– density at 20 C kg/l	1
	HEAVY FUEL HFO 380	– calorific value kJ/kg	41000
		– density at 20 C kg/l	1

TEST	POWER		SPEED				MEASURED FUEL			CONSUMPTION	SPECIFIC CONSUMPTION		
							AMOUNT	LEAKAGE	TIME		MEASURED	CORRECTION FROM ISO+CAL.VALUE	
no	%	kW	. rpm	T1	T2	P1	kg	kg	min	kg/h	g/kWh	FUEL	g/kWh
1	25	3194	500	33	38	758	50	1.21	4.74	617.6	193.4	MDO	190.6
2	50	6336	500	36	38	758	100	1.80	5.05	1166.7	184.1	MDO	181.1
3	75	9440	500	34	38	759	200	2.59	6.87	1724.1	182.6	MDO	179.9
4	100	12598	500	33	38	759	300	3.03	7.65	2329.2	184.9	MDO	182.2
5	85	10718	500	36	38	759	200	0.20	6.01	1994.7	186.1	HFO	176.2
6	100	12600	500	36	37	759	300	0.29	7.64	2353.7	186.8	HFO	176.9
7	110	13860	500	36	34	759	300	0.47	6.80	2642.9	190.7	HFO	180.9
8	0	0	0	0	0	0	0	0.00	0.00	0.0	0.0	MDO	0.0
9	0	0	0	0	0	0	0	0.00	0.00	0.0	0.0	HFO	0.0
10	0	0	0	0	0	0	0	0.00	0.00	0.0	0.0	HFO	0.0

K = 0.000
ALFA = −0.17
BETA = 0.000

K = (P1/750)^0,7 * (298/(273+T1))^1.2 * (298/(273+T2))^1

ALFA = K−0,7*(1−K)*(1/0,8−1)

BETA = K/ALFA

$$\text{CORRECTED FUEL CONSUMPTION} \quad \frac{\text{MEASURED CONSUMPTION}}{\text{BETA}} * \frac{\text{ACTUAL CAL.VALUE}}{42700}$$

Appendix G

Fuel specifications

Calculation of weight percentages:

The C/H ratio is estimated at 7.5 for this research. The following calculation leads to the weight percentages that can be used as average values in this research:

$x_C = 97/8.5 * 7.5 = 85.58$
$C/H = x_C^f / x_H^f$

$7.5 = x_C^f / x_H^f$
$x_C^f = (1-x_S^f) / (1+ C/H) * (C/H)$
$x_C^f = (1-0.03) / (1 + 7.5) * (7.5) = 0.8558$

$x_H^f = (1-x_S^f) / (1 + C/H)$
$x_H^f = (1-0.03) / (1 + 7.5) = 0.1141$

Weight percentages
x_C^f = 86 %
x_H^f = 11 %
therefore x_S^f = 3 %

General fuel specifications:

The table below contains the general fuel specifications from Boskalis IFO 380

Parameter		Unit	Specification	ISO Method
Density at 15 deg.C.	Max	kg/m3	991.0	ISO 3675 or ISO 12185
Viscosity at 50 deg.C.	Max	mm2/s	380	ISO 3104
Sulpher	Max	% (m/m)	3.0-3.5	ISO 8754
Flash point	Min	deg.C.	60	ISO 2719
Pour point	Min	deg.C.	6	ISO 3016
Pour point	Max	deg.C.	30	ISO 3016
Micro Carbon Residue	Max	% (m/m)	15	ISO 10370
Water	Max	% (v/v)	0.5	ISO 3733
Total sediment potential	Max	% (m/m)	0.10	ISO 10307-2
Ash	Max	% (m/m)	0.10	ISO 6245
Vanadium (V)	Max	mg/kg	100	ISO 10478 or ISO 14597
Aluminium (Al) + Silicon (Si)	Max	mg/kg	20	ISO 10478
Sodium (Na)	Max	mg/kg	30	ISO 10478
Zinc (Zn)	*Max*	*mg/kg*	*15*	*ISO 10478*
Phosphorus (P)	*Max*	*mg/kg*	*15*	*ISO 10478*
Calcium (Ca)	*Max*	*mg/kg*	*30*	*ISO 10478*

Calculation of emission factor:
Below the calculation of the emission factor of CO_2 using the kmol ratio is and the calculation using the mass ratio and the estimations of fuel weight percentages is described:

kmol ratio

$$nr_{CO_2}^{g\text{-}out} = \frac{x_{C_f}}{M_C}$$

$$nr_{CO_2}^{g\text{-}out} = \frac{0.86}{12} \text{ [kmol/kg fuel]}$$

mass ratio

$$mr_{CO_2}^{g\text{-}out} = \left(\frac{M_{CO_2}}{M_C}\right) x_{C_f} \text{ [kg/kg fuel]}$$

$$mr_{CO_2}^{g\text{-}out} = \frac{44}{12} 0.86 \text{ [kg/kg fuel]} = 3.153333 \text{ [kg } CO_2\text{/kg HFO with } x_{C_f} = 86\% \text{]}$$

$$m_{CO_2}^{g\text{-}out} = m_f * mr_{CO_2}^{g\text{-}out}$$

Appendix H

Variables

List of variables
A = Air ratio [%O_2, Nitrogen]
C = Costs [$]
C_{em} = Costs emissions [$ /m^3]
C_f = Costs fuel [$ /m^3]
C_{op} = Costs operational [$ /m^3]
D = sailing distance [m]
k_i = constant
M = Molecular weight
m = Mass [g]
$m_{em}^{g\text{-}out}$ = mass emissions gas produced [g]
mr = Mass ratio [%]
N = Power [kW]
n = Number of kmol
S = Pitch [%]
P = Price [$]
P_{em} = Price of emission gas [$ /g]
P_f = Price of fuel [$ /l]
P_{op} = Price of time [$ /s]
T = Temperature [K]
H = Time needed [s]
U = Fuel consumption [l]
V = Volume of dredged material [m^3]
v_w = Vessel speed through water [kn]
x = Mass fraction [%]

Subscripts:
C = Carbon
O = Oxide
CO_2 = Carbon Dioxide
f = Fuel
g-out = gas output
prop = propeller
p = production
S = Sulphur
SO_x = Sulphur Oxides
N = Nitrogen

NO_x = Nitrogen Oxides

List of logged variables in SCADA
Below all variables that were logged on board via the SCADA system are listed. The variables can be found in the 'BOKA table' available on board the Queen of the Netherlands.

Steering variables:
- Requested pitch (Pitch) → S (%)
- Number of main engines running → M [0,1,2]

Response variables:
- Fuel consumption
    - Fuel consumption with fuel meter → U
    - Position of plunjer → h
- Total time (cycle phase) → t_p (s)
- Delivered power propellor → N
- Delivered power generator → N_g
- Delivered power dredging pump → N_d
- Sailing speed
    - On ground (GPS) → v_{gps} (m/s)
    - Through water (logsnelheid) → v_w (m/s)
- Sailing speed during dredging
    - On ground → $v_{d.gps}$ (m/s)
    - Through water (log speed) → $v_{d.w}$ (m/s)
- Discharge speed
    - Speed material → v_p (m^3/s)

Environment variables:
- Positioning of ship in water (depth) → d (m)
- Density material → ρ (g/m^3)
- Rudder angles → R (º)
- Water dept → w (m)
- Blower frequency
- Temperature air inlet
- Pressure air inlet
- Temperature air exhaust

Appendix I

Verification and validation

Verification
The verification of the model was conducted by carrying out an extreme values analysis and a sensitivity analysis. This appendix describes examples of these analyses.

Example extreme values analysis:

INPUT		OUTPUT	
Pitch capacity	0	Emission costs	0
Emission price	10	Fuel costs	0
Fuel price	500	Operation costs	2000
Price operation time	2000	Total costs	2000
Price DM	5	Profit	-2000
		NO_x	0
		SO_x	0
		CO_2	0

Example sensitivity analysis:

INPUT		OUTPUT	
Pitch capacity	+/- 0%	Emission costs	+/- 10%
Emission price	+/- 10%	Fuel costs	+0%
Fuel price	+/- 0%	Operation costs	+0%
Price operation time	+/- 0%	Total costs	+ / - 3%
Price DM	+/- 0%	Profit	+ / - 3%
		NO_x	+ 0%
		SO_x	+ 0%
		CO_2	+ 0%

Validation
The validation of the model was conducted by comparing calculated values for fuel consumption to the manually measured daily averages. This appendix describes an example of this validation based on experience numbers.

The model generates an output for maximum operation during sailing loaded of 0.9 [kg HFO/s] fuel consumption for the propulsion of the vessel (thus excluding the fuel required to deliver power to the main generator).

0.9 * 86400 = 77760 [kg/day] for the propulsion if the vessel would sail at maximum capacity for 24 hours. 77760 kg is 67 MT (using density 991 [kg/m^3])

This value has a correct order of magnitude since the numbers of registered fuel consumption by Boskalis lie around 80 MT/day.

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