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Master Thesis

EXPLORING A DECISION FRAMEWORK FOR EVALUATING COST-EFFECTIVENESS AND UTILITY OF CO_2 ABATEMENT MEASURES IN SHIPPING

-A METHODOLOGY APPLIED TO THE CASE FLEET OF GRIEG SHIPPING GROUP

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PREFACE

This thesis was written as a requirement for completing the Master of Science degree in Marine Technology during the spring of 2010. The assignment was completed in cooperation with Grieg Shipping Group and DNV Research and Innovation.

The main objective of the study was to explore methods for evaluation and selection of greenhouse gas abatement measures for a specific fleet of ships.

I learned as I went along in the process of writing this thesis, and I believe I eventually found my way in a jungle of fancy words, intimidating authors, and strong opinions.

During my five years as a student I have been taught to have a healthy scepticism and to be critical about information presented to me. In a way I feel that I have learned how to learn. However, acquiring knowledge yourself is one thing - passing it on to others is quite another, and is much more demanding. Nevertheless, I feel I was somewhat successful at conveying information about abatement measures and decision analysis during my case study, and, I hope I can do the same in this paper.

My main thanks go to professor Stein Ove Erikstad for his guidance and constructive feedback during these past 6 months. I would also like to thank the Senior Project Engineers Aage Oscar Langeland and Olaf Tronvold for the help they gave me in collecting information regarding the Grieg ships. Many thanks as well to Magnus Strandmyr Eide, senior researcher at DNV Research and Innovation, who assisted me greatly by providing valuable cost data.

Trondheim, Monday, June 14, 2010

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Cecilia Girard

ABSTRACT

Selecting greenhouse gas abatement measures for a specific fleet of ships is not an easy task and many factors are to be considered by ship operators. Current methodologies for assessing measures are based on cost-effectiveness evaluations. The main aim of this paper is to explore new ways to evaluate and select greenhouse gas abatement measures in shipping.

To address this, a case study regarding the open hatch bulk fleet of Grieg Shipping Group is presented in order to illustrate the decision problem. In this case, 25 abatement measures were evaluated for cost effectiveness and reduction effect using current methodology in combination with a qualitative 'utility' assessment of the measures.

Existing marginal abatement cost methodology was used to evaluate the cost-effectiveness of the chosen abatement measures. It was found that 37% of the current greenhouse gas emissions of Grieg ships were abatable in a cost efficient way, using multiplicative aggregation. The savings potential was estimated to reach an annual amount of 1,5 million $ per year per ship.

The cost–effectiveness assessments was added to a qualitative 'utility' assessment using a methodology called Multi Criteria Decision Analysis. For each measure, this decision analysis included qualitative utility criteria such as safety considerations, technical maturity and complexity. Employees of Grieg Shipping Group were used both to score the performance of each alternative and to attribute weights of preference to the different criteria.

The results of the analysis yielded a cost-effectiveness ranking and a utility ranking. These two rankings were then aggregated in a Marginal Abatement Utility and Cost chart (MAUCC) where all three parameters; cost-effectiveness, utility score and reduction effect are presented at the same time(Figure 37). This chart can be seen as the primary outcome from the adopted decision framework, and summarizes a lot of information without overly simplifying. Its results as well as its use are discussed in chapters 5 and 6.

In this case study, some measures were found to have high ratings for both utility and cost-effectiveness ("1-Voyage execution", "9-Propeller condition", "4-Engine monitoring", "5-Reduction of aux. power" and "7-Trim/draft optimization"), while the more emerging abatement measures represented a higher reduction effect, but also lower cost – and utility scores (See "21-Kite" and "22-Fixed sails" or "12-air cavity lubrication"). It is suggested that increased research on emerging abatement measures could increase their qualitative "utility scores". Using the MAUCC chart it is shown that these new and exciting alternatives do not all need large qualitative improvements before they become viable alternatives for emission reduction.

A discussion on the obstacles to implementation of seemingly cost effective abatement measures is also conducted, and it is shown that the main factors identified by Grieg employees were circumstances related to the organization and uncertainty about pricing and benefit of abatement measures.

Discussion on the main findings as well as suggestions for further study is conducted in chapters 5, 6 and 7.

ABBREVIATIONS

GHG	Greenhouse Gas
CO_2	Carbon Dioxide
SO_x	Sulphur oxides
NO_x	Nitrogen oxides
EEOI	Energy efficiency operational indicator
EEDI	Energy efficiency design index
MEPC	Marine Environmental Protection committee
IPPC	Intergovernmental Panel on Climate Change
IMO	International Maritime Organization
MCDA	Multi Criteria Decision Analysis
DM	Decision Maker
CATCH	Cost of Averting a Ton of CO_2-eq. Heating
MARPOL	Marine Pollution "International Convention for the Prevention of Pollution from Ships"

CONTENT

FIGURES

TABLES

INTRODUCTION

Reduction of greenhouse gases has recently attracted increased attention and has been placed on the international agenda. (IMO GHG study, #1) An international scientific consensus has been reached regarding human influence on global warming, and policy makers have concluded on an attempt to limit the increase by 2°C increase. (Reuters, 2009, #2).

The Intergovernmental Panel on Climate Change has stated that developed countries have to reduce emissions by 25-40% below 1990 levels by 2020, and 80-95% below 1990 levels by 2050 in order to stabilize atmospheric greenhouse gases to 450 ppm CO2-eq.((IPPC), #3). And even with these ambitious goals, there is still disagreement on if this is sufficient to avoid dangerous anthropogenic interference in the climate.

All countries are called upon to make a contribution in an effort to turn around the development and limit the impact on climate change. Shipping, as an international industry, will also need to bear its share of the burden as international shipping represents about 3% of anthropogenic GHG emissions. Many are now sensing the possibility that policy makers are interested in introducing marked based incentives to regulate carbon emissions from shipping.

A lot of work has been done to investigate the current emission level from international shipping and evaluate a realistic reduction potential for greenhouse gas emission in future growth scenarios. The results suggest that a range of technical and operational measures could increase efficiency and reduce the emissions rate by 25% to 75% below current levels (IMO GHG study, 2009, #1).

"There is high agreement and much evidence that all stabilization levels assessed can be achieved by deployment of a portfolio of technologies that are either currently available or expected to be commercialized in coming decades, assuming appropriate and effective incentives are in place for their development, acquisition, deployment and diffusion and addressing related barriers."((IPPC), #4)

Much of the work regarding greenhouse gas emissions from ships is focused on debating how to develop policy options, and papers dealing with abatement measures are primarily directed towards the whole world fleet on a general basis. Even if no regulations have been officially announced, environmentally focused ship operators are struggling to choose strategies on how to reduce carbon emissions. Within this context several studies have been carried out in order to assess different abatement measures to reduce carbon emission from ships. However the task of choosing and adopting these abatement measures is not an easy one for ship operators. The decisions require consideration of several uncertain factors like cost-effectiveness, feasibility, compatibility, and abatement potential. These factors are complex and difficult to evaluate all at once, especially as they vary significantly with ship variables such as type, size and age

PURPOSE OF STUDY

This study is an attempt to help ship operators in their decision making with regards to the evaluation and selection of GHG abatement measures. The main part of my work is a case study completed in cooperation with Grieg Shipping Group where I develop a decision framework applicable for considering greenhouse gas abatement options. This framework applies existing methodology to assess the cost-effectiveness of abatement measures, but also, it introduces new qualitative criteria beyond the cost effectiveness which could affect which options are chosen. The aim of the case study is to explore the contribution and effect of utilizing such a formal decision framework with special focus on how the overall utility of an abatement options can be appraised.

Upon starting the case study, the overlying question I attempted to answer was: How can a vessel operator decide which strategy to employ in reducing carbon emissions in his fleet?

Underlying questions related to this were:

- How can a ship operator identify all relevant abatement options to reduce carbon emissions from his fleet?
- How can a ship operator choose amongst the various existing alternatives?
- Does a systemized approach exist which aids priority ranking of abatement measures?
- Is cost the only discriminating criteria or are there other values of effectiveness?
- If some of the measures are cost-effective (negative cost), why are they not implemented?

STRUCTURE OF STUDY

1 The paper will first present some background information on sustainable ship design and operation. An attempt is made to identify abatement measures and create a taxonomy to categorize different types of options. I also review existing methodology for assessing the cost effectiveness of different abatement measures.

2 I then present a basic approach to multi criteria decision theory and develop a decision framework to assess abatement measures according to different criteria beyond cost effectiveness.

3 The case study addresses 25 technical and operational measures which are to be evaluated for Grieg's open hatch bulk carrier fleet. The measures are evaluated in terms of utility and cost–effectiveness. The qualitative utility evaluations are made according to 4 qualitative attributes and employees in Grieg Shipping Group score the performance of each alternative and attribute weights of preference to the different criteria.

4 In section 4 I present some general barriers to the implementation of cost efficient abatement measures.

5 Finally I discuss the outcome of the decision model and the main findings in my study.

1 BACKGROUND INFORMATION

This chapter offers an introduction to the concept of sustainable ship design and operation with special focus on green house gas emissions and low carbon shipping. I will present the main existing and emerging measures for reducing GHG emissions from ships as well as the existing methods used to evaluate the cost effectiveness of these measures.

1.1 EMISSIONS FROM SHIPPING

Ships have released harmful emissions to both air and sea ever since the first steamboat took to the waves in the late 18th century. Robert Fulton was the first to operate steamboats commercially, and in 1807 the first commercial steamboat began passenger service between New York City and Albany, New York, a service which enjoyed great success. (MIT school of engineering, 2010, #5)

Figure 1: Fulton presents his steamship to Bonaparte in 1803.

Historically oil pollution from ships was the first topic which began to raise attention in the first half of the 20th century. In the 1920s a number of countries introduced national regulations to control discharges of oil in their territorial waters. (Llyod's register, 2010, #6)

Following that, however, not much action was taken until 1973, when the first international legislation on ship emissions was adopted. MARPOL , the convention addressing the problem of marine pollution was introduced by the Inter-Governmental Maritime Consultative Organization, later known as the IMO (International Maritime Organization).

MARPOL covers all types of pollution caused by both operational and accidental emissions, and the MARPOL protocol has been regularly updated in form of additional annexes for regulation of several types of harmful polluters. Figure 2 shows the main emissions from shipping (Erikstad, 2009, #7)

Pollution to air:

- Exhaust gas from machinery
- Evaporation from cargo

Pollution to sea:

- Sewage and garbage
- Operational oil spills
- Accidental oil spills
- Antifouling paint
- Bilge water and tank washing
- Ballast water as organic compounds

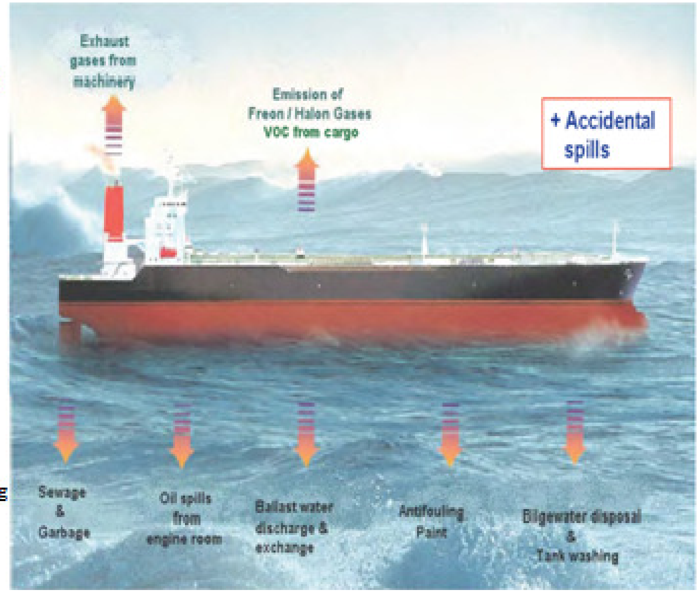


Figure 2: Overview of main emissions from ships

The last amendment to the MARPOL protocol is Annex VI regarding air pollution from ships with special focus on Sulphuric and Nitric Oxides. Emissions are covered in more detail in the following sections.

Currently MARPOL includes these annexes:

- Annex I: Regulations for the Prevention of Pollution by Oil
- Annex II: Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk
- Annex III: Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form
- Annex IV: Prevention of Pollution by Sewage from Ships
- Annex V: Prevention of Pollution by Garbage from Ships
- Annex VI: Prevention of Air Pollution from Ships(Llyod's register, 2010, #6, IMO, 2009, #8)

1.1.1 EMISSIONS TO AIR- SO_X , SO_X AND GREENHOUSE GASES

In the discourse on air pollution from ships, machinery exhaust gases have gotten the most attention lately. The main hazardous gases emitted from the engine combustion chamber to the atmosphere are NO_x, SO_x, greenhouse gases and particulate matter. (IMO GHG study, #1). A brief introduction to each of these pollutants is given in the boxes below:

1.1.1.1 NO_x

Composition: mainly NO_2 and NO

Effects on human health: NO_x can react with other compounds to form nitric acid, particles and ozone. Inhalation of such compounds may lead to respiratory problems and lung diseases.

Effects on environment: NO_x emissions can directly or indirectly cause acid rain or smog, and can unbalance ecosystems by depleting oxygen in water or increasing levels of toxin harmful to aquatic life.

Formation: NO_x is formed inside the engine combustion chamber at high temperatures. N_2 and O_2 are gases naturally present in the atmosphere but when they are exposed to the high temperatures during the combustion process they form different types of nitric oxides.

How to reduce: Possible ways of reducing the formation of NO_x are to reduce the temperature, reduce the oxygen or reduce the residence time in the engine combustion chamber.

Contribution from shipping: about 10-15% of the global NO_x emissions.

Regulations: NO_x emissions from ships are regulated by MARPOL 73/78 Annex VI.

1.1.1.2 SO_x:

Composition: mainly SO_2 and SO_3.

Effects on human health: SO_x may lead to respiratory problems and lung diseases.

Effects on environment: SO_x are contributors to acid rain.

Formation: The SO_x gases are formed in the combustion process, where sulphur from the fuel reacts with oxygen from the intake air during combustion.

How to reduce: The only way of preventing the formation of SO_x in the combustion process is to use fuel containing less sulphur. However it is possible to reduce the amount of sulphur oxides reaching the atmosphere by using the After Treatment Scrubber Technology where the exhaust gas is mixed with water vapor which absorbs the sulphuric emissions.

Contribution from shipping: about 4-9% of the global emissions.

Regulations: SO_x emissions from ships are regulated by MARPOL 73/78 Annex VI.

1.1.1.3 Greenhouse Gases

Composition: mainly CO_2 but also methane CH_4, N_2O, HFC's PFC and SF_6.

Effects on environment: Contributors to dangerous anthropogenic interference in climate and sea level rise.

Formation: The main green house gas (CO_2) is formed in the combustion chamber of the engine where the carbon in the fuel reacts with oxygen in the air.

How to reduce: The most common way to reduce the formation of CO_2 is to use less fuel or to use fuel with less fuel cycle carbon emissions. Measures for capturing and storing CO_2 onboard ships is not a feasible solution.

Contribution from shipping (CO_2): about 3% of the global anthropogenic CO_2 emissions.

Regulations: CO_2 emissions from ships are at present time not regulated.

This study focuses is on GHG-emissions. Below is a systemized scheme which represents different issues related to GHG emissions from shipping.

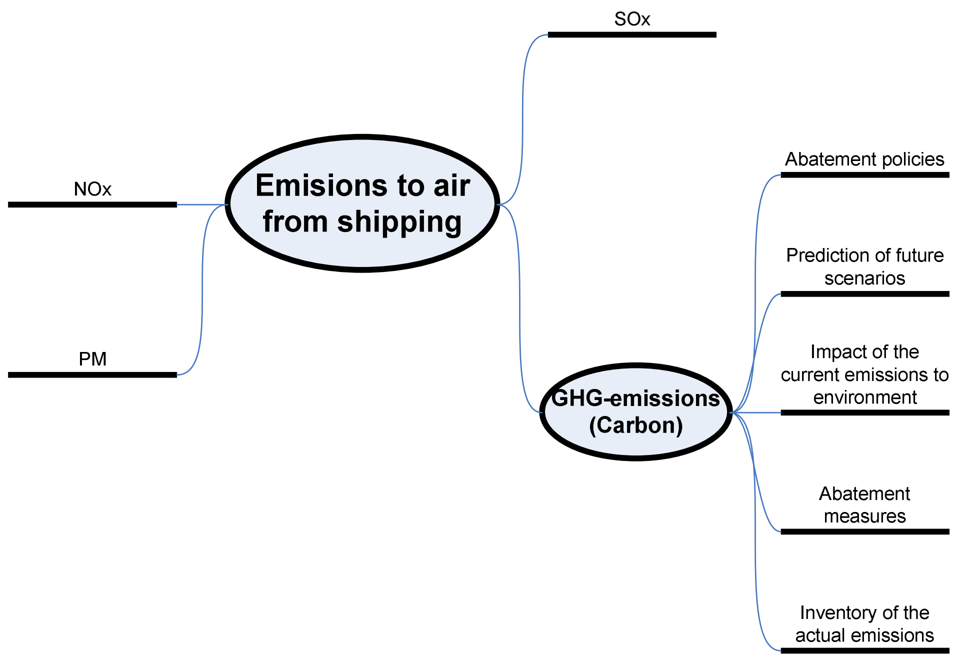


Figure 3: Systemized representation of emissions to air

References:(Erikstad, 2009, #7) (IMO GHG study, 2009, #1) (IPCC, 2007, #9)(US environmental protection agency, 2009 #23))

1.2 Low carbon shipping

Even though transport by sea produces less carbon emissions per ton/km of cargo compared to other transport modes, the shipping industry is under mounting pressure to reduce GHG-emissions. IMO finds that shipping in total represents 3,3 % of the global CO_2 emissions during 2007(IMO GHG study, 2009 #6). This amount corresponds to as much as 1,046 million tons of CO_2 per year. To illustrate this, if shipping was a country, it would be placed in the list next to the main emitting countries like Germany or India. As such, considerable efforts are being made by IMO to develop technical, operational and financial measures to regulate carbon emission from ships. The Marine Environmental Protection Committee (MEPC) at its 59th session proposed guidelines to calculate Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operational Indicator (EEOI). These are indicators for voluntary use aimed at defining a ships capability of emitting CO_2 in relation to the effective transport work (IMO MEPC. 1 Circ. 683, 2009, #10, IMO MEPC. 1 Circ. 684, 2009, #11, IMO MEPC. 58/4/34, 2008, #12). However shipowner associations believe that the best way to achieve a real and lasting reduction in CO_2 emissions from shipping is through a global and open emission trading scheme (The Chamber of Shipping, 2009, #13).

Furthermore, environmentally oriented shipping companies are continuously seeking solutions to mitigate GHG emissions from ships. Literature regarding the GHG emission from shipping is discussed further in the next section.

1.2.1 Literature review

The IMO GHG study (IMO GHG study, 2009, #1) is currently seen as the main source of information related to the holistic assessment of GHG emissions from shipping. This study includes a thorough inventory of the current level of GHG emissions from ships, with an investigation of how the emissions will evolve in future scenarios. The achieved reduction in NO_x and SO_x emissions by implementing the MARPOL protocol is also discussed together with an overall evaluation of the climate impact from ship emissions. The report also presents relevant policy options for reductions of GHG-emissions and compares ship transport with other transport modes. More action oriented, the IMO GHG study presents the technical and operational potential of GHG emissions reduction on the world fleet towards 2050. Here, a set of operational and technical abatement measures are addressed - each with an estimate on abatement potential and cost effectiveness.

One of the main outcomes from the IMO GHG-study is the identification of a significant reduction potential through technical and operational measures. The potential has been identified to reach a possible level of 25% to 75% of GHG-emission reduction below the current emission levels; and much of the reduction is possible to implement in a cost-effective manner.

Other institutions and organizations like OECD, ICCT, UK Department of Transport and International transport forums (Crist, 2009, #14, ICCT, 2007, #15, Melanie Hobson, et al., 2007, #16)have done studies evaluating the possible GHG emission reduction potential of ships using different emission reduction strategies. A common characteristic of these papers is their identification of existing operational and technical abatement strategies. In the reviewed papers, the abatement potential and the overall properties of one or several abatement options are discussed and evaluated. However researchers tend to look at different selections of abatement options each time and they are rarely consistent in their choice of abatement technologies. Moreover, the research done on the matter is highly limited by the lack of reliable data, and estimations about reduction potentials are often rough. The characteristics of abatement measures are often specific to the ship type- and size and are difficult to address in a general scenario.

Furthermore, most of the previous studies on GHG abatement measures have been aimed at analyzing policy options that are relevant to the debate on regulation of ship GHG emissions.

The industry is now claiming a more hands-on approach to the decision problem of evaluating and selecting abatement strategies in shipping. The emphasis is set on factors like cost effectiveness, technology, uncertainty and organizational or technical considerations related to the process of implementing different abatement measures. Even though much work has been invested both from academia and the industry in the matter of GHG-emission control in shipping, there is still much to be done in this area in order to make shipping companies confident and comfortable in taking decisions about investments in abatement measures.

1.2.2 *IDENTIFICATION OF MEASURES WHICH REDUCE CO_2 EMISSIONS FROM SHIPS*

The different abatement measures to reduce carbon emissions from ships are widely diversified in nature. Many of the different measures have little in common and are difficult to compare to one another. The nature of an abatement measure could be anything from a small technical installation to an extensive operational management change which could affect the shipowner organization as a whole. Since much of the existing literature evaluating different abatement measures differs in the choice of abatement options to evaluate, this part of the study is an attempt to map and categorize the different measures to reduce carbon emissions from ships. Below is a systemized scheme of ideas related to identification process.

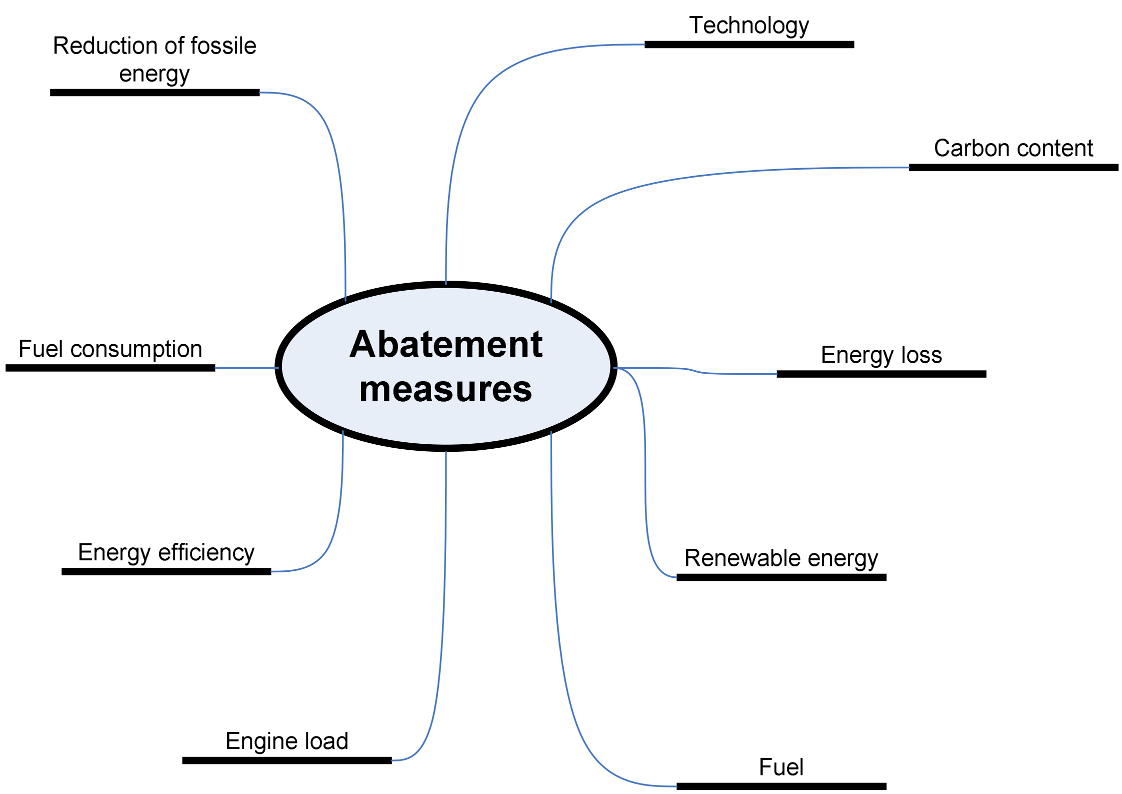


Figure 4: Systemized scheme of ideas related to the identification of abatement measures

1.2.2.1 What is an abatement measure

An abatement measure is simply stated a measure which in some way reduces a ships emissions. However, it is not easy to state an overall definition of the concept. A measure could be defined as a new technology, a strategy or a change in any operational routines of the vessel. Roughly one can say that abatement measures are either acting on the concept of reducing overall fuel consumption or are targeted towards a specific emission type. In this study, only carbon emission will be treated, and consequently abatement measures which are targeted towards reduction of SO_x and NO_x only, are not included.

An identification of all abatement strategies for reducing a ships carbon emissions can be approached in different ways. A common representation for systemizing the different options is to divide the overall possibilities in four different paths to achieve low carbon ships. (IMO GHG study, 2009, #1)

1. Improving energy efficiency: Reducing fuel consumption by reducing energy losses
2. Using renewable energy: Reducing fuel consumption by adding renewable energy sources
3. Using fuel with less fuel cycle emissions: Reduce carbon emissions by using fuel with less carbon content
4. Capture and storage technologies: Filter out the carbon emissions from the exhaust gases

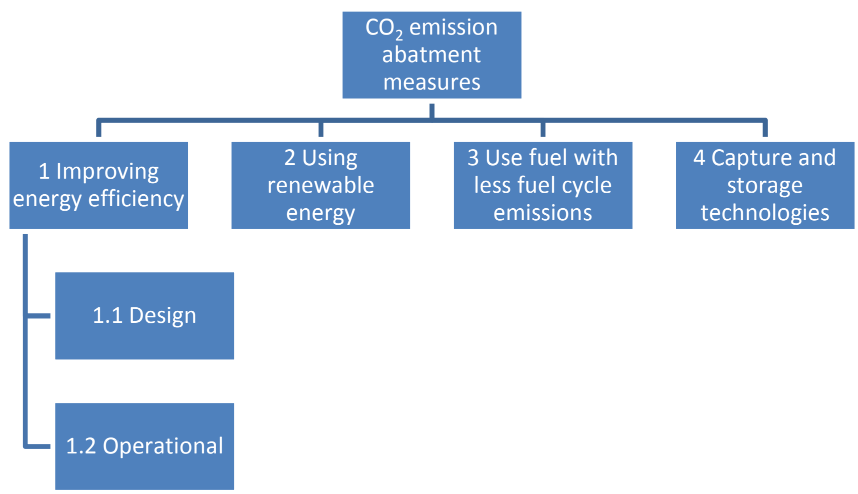


Figure 5: Systemized categorization of carbon emission abatement measures

Storage of CO_2 would require an extensive and unreasonable amount of space and deadweight on a ship voyage and the technology for capturing CO_2 has not yet been developed for use on ships. This paper focuses on practical application, and even though technical feasibility studies on carbon capture and storage are current and interesting, they are beyond the scope of this paper.

The seemingly most promising pathway to lower carbon emissions from ships is the improvement of the ship's energy efficiency. This is due to the high cost effectiveness of these measures since they tend to save fuel cost. However the use of renewable energy is not to be neglected in spite of its young technology.

1.2.2.2 Energy efficiency

The path of improving energy efficiency is the most common way of reducing fuel consumption and thus CO2 emissions. The energy efficiency of ships has historically increased with time as technology has improved. As seen in Figure 6 from the IMO GHG-study, the overall energy efficiency of today's ships are estimated to continue to have a steady increase in the future.

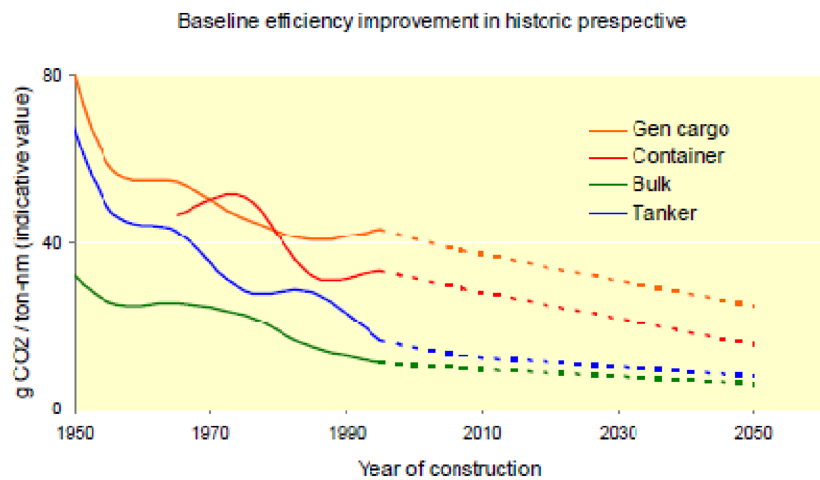


Figure 6:Future prediction of energy efficiency improvement in shipping(IMO GHG study, 2009, #1)

An increase of a ships energy efficiency is a requirement in order to use less fuel for achieving the same amount of transport work, in other words to minimize the energy loss of the ships energy system. The energy loss in a ship propulsion system occurs in different stages of the energy transport all the way from the specific energy in the fuel to the induced kinetic energy in the water. The figure below represents a typical distribution of the energy transport onboard a small cargo ship, head sea, Beaufort 6.(IMO GHG study, 2009, #1)

The objective of increasing efficiency could in this figure be illustrated as a maximization of the white areas and a minimization of the coloured areas in order to reduce the losses of the propulsion power.

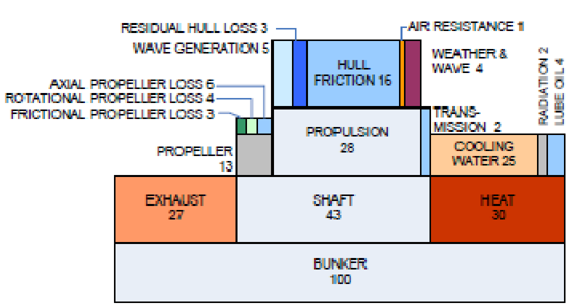


Figure 7: Typical energy balance onboard a small cargo ship(IMO GHG study, 2009, #1)

With Figure 7 in mind, the options for energy efficiency improvement can be divided further into different underlying groups as each coloured block represents losses which could be reduced to improve the energy efficiency. While some methods for example deal with the ability to reduce ship friction, others may act on the possibility to reduce propeller losses. One can imagine that abatement measures from different coloured blocks are likely to be aggregated without risks of redundancy or affecting the total abatement potential. Abatement measures from the same coloured block however, would most likely not be aggregated without affecting the total sum of abatement potential.

To categorize further, the energy efficiency options could again be separated into two underlying groups; technical options and operational options. The technical/design options are related to the ships technical ability to do a certain transport work at a certain service speed while utilizing a specific amount of fuel. In other words it represents the ships optimal designed energy balance as seen in the Figure 7.

The operational group is more related to the crew and the ship operators ability to maintain the initial level of fuel consumption for the expected deadweight and speed. Often the ship is not operated in optimal conditions and efficiency is reduced due to human operation and degradation of equipment.

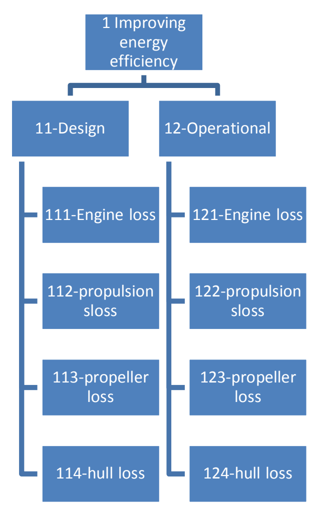


Figure 8: Systemized categorization of abatement measures included in the group of energy efficiency

An attempt to present a taxonomy of abatement measures related to energy efficiency measures is shown below.

Table 1: Taxonomy of abatement measures related to energy efficiency

1 Energy efficiency								
11 Design				12 Operational				
111	112	113	114	121	122	123	124	125
Decrease engine loss	Decrease transmissions loss	Decrease propeller loss	Decrease hull resistance	Maintain optima engine loss	Maintain optima transmissions loss	Maintain optima propeller loss	Maintain optimal hull resistance	Reducing service speed

In addition to the taxonomy above, a segregation of main engine efficiency and auxiliary energy efficiency is appropriate.

1.2.2.3 Using fuel with less fuel cycle carbon emissions

CO_2 emissions from ships can also be cut by switching to fuels with lower total carbon emissions. Fuel types of interest in this regard include biofuels and natural gas. Regarding biofuels, the net benefit in CO_2 emissions differs among different types of biofuels and also with the method used to produce the fuel itself. The net CO_2 benefit could be quite small and in certain cases the use of biofuels have resulted in a 7% to 10% increase in NOx emissions. Overall, the present potential for reducing CO_2 emissions from ships by use of biofuels is estimated to be quite limited.(IMO GHG study, 2009, #1)

The use of natural gas onboard ships has on the other hand been widely adopted. The gas has a higher hydrogen-to-carbon ratio compared with oil-based fuels, and the benefits are many, considering that NO_x and SO_x-emission are almost completely absent using natural gas as fuel. However the main challenge of using natural gas on ships is to find sufficient space to store the fuel onboard. Another factor which has to be evaluated is the limited bunkering facilities available in ports.(IMO GHG study, 2009, #1)

1.2.2.4 Renewable energy:

Renewable energy is also a method of reducing carbon emissions from ships, either by direct use onboard the ship (wind or solar power) or by cold ironing which is the process of providing shore-side electrical power to a ship at berth while its main and auxiliary engines are turned off. However the energy from cold ironing power could also originate from fossil energy sources.

Onboard use of wind power can mainly be utilized in three ways; sails, kites and Flettner-type rotors. The wind power availability varies to a large extent with the climate and thus some routes can utilize wind power better than others. Overall the present day development of all wind power related technologies is still in an emerging phase. The use of wind power onboard large vessels is still quite limited whereas it has been tested out and is currently commercially advancing in the smaller vessel segments. The potential typically represents a main engine power cut from 5% - 20% depending on the routes, the speed and the ship size.(IMO GHG study, 2009, #1)

Onboard use of solar power represents a much smaller potential than wind energy and supplies only a fraction of the required auxiliary power needs. The restricted availability of deck area is the main reason for this limited benefit. However solar power has been installed commercially on some ships. (IMO GHG study, 2009, #1).

1.2.2.5 Identification results

As a result of the identification of GHG abatement measures in shipping, an attempt to construct a taxonomy for categorizing GHG-abatement measures has been made. All existing measures should in theory be placed in one and only one category box.

Table 2: Taxonomy to categorize abatement measures

1 Energy efficiency		2 Renewable energy		3 Fuel changes	4 Capture
11 Design	12 Operational	21 Wind power	22 Solar power	31 Fuels with less fuel cycle emissions	41 Storage of CO2

1.2.3 COST-EFFECTIVENESS ASSESSMENT OF ABATEMENT MEASURES-LITERATURE REVIEW

Even though GHG abatement measures is a relatively new topic in shipping, the concern of improving energy efficiency has been on the agenda for quite a long time due to its potential to save costs. However with the consensus on climate change and emerging focus on reducing CO_2 emissions the interest has increased and new methodology to systematically evaluate the cost-effectiveness of reducing GHG-emissions has been developed.

The main previous studies dealing with the topic of cost-effectiveness evaluation of abatement measures include;

1. Second IMO GHG Study, 2009, (Chapter 5)(IMO GHG study, 2009, #1)
2. Cost effectiveness assessment of CO_2 reducing measures in shipping, (Eide, 2009, #17)
3. Pathways to low carbon shipping,(DNV, 2009, #18)

The development of the CATCH-parameter (Cost of Averting one Ton of CO_2-eq. Heating unit) and the MACC (Marginal Abatement Cost Curve) could be regarded as the main outcome of these studies in means of methodology to estimate cost-effectiveness of abatement measures.

The CATCH parameter, is a factor describing the cost of averting one ton of CO_2 eq. heating. The unit is most commonly $\left[\frac{\$}{ton\ CO_2}\right]$ and the value could either be positive or negative, depending on the cost and the fuel savings of the abatement measure. The CATCH parameter provides a basis for comparing the unit costs of several abatement measures without consideration to the reduction effect of each measure.

Eide et al. (Eide, 2009, #17) present the CATCH parameter by comparing the cost effectiveness of 13 different abatement measures. In Eide's cost effectiveness approach, he applies the 13 measures on two specific ships; a bulk carrier and a container ship. The aim of his paper is to develop a decision criterion, the CATCH, to be used when assessing the cost effectiveness of technical and operational measures to reduce CO_2 emissions. However the focus of his paper is mainly to contribute to the future regulatory process regarding shipping emissions and not to assist shipowners in selecting abatement measures. The result of the study suggests that a CATCH value of 50 USD/ton CO_2 should be used as a decision criterion for investment in emission reduction measures in shipping. To illustrate, the obtained CATCH-value for the 13 abatement options applied to the bulk carrier are shown below in Figure 9.

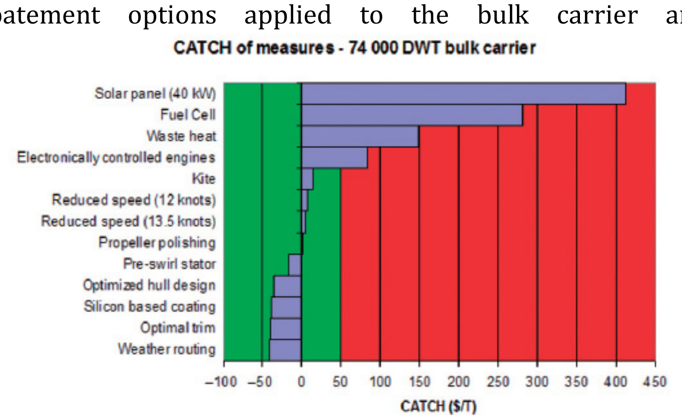


Figure 9: CATCH-values for emission reduction measures applied to a Bulk(Eide, 2009, #17)

The IMO GHG study addresses 25 operational and technical measures where data could be obtained in their cost/benefit approach to assess abatement measures. The CATCH parameter has been computed for each of the selected measures to represent the total world fleet abatement potential to 2020. The aggregated plot of CATCH parameters is called Marginal Abatement Cost curve (MACC) and gives a good representation of both the cost-effectiveness and the aggregated reduction effect of the different measures (Figure 10). The main aim in computing this curve is to answer the question "How much emission could possibly be reduced and at what cost?"

In this MACC- plot the x-axis represents the accumulated emission reduction effect in tons of CO_2. The different abatement measures are addressed along the x-axis, with varying width according to their reduction effect along the x-axis. The measures are horizontally sorted with regards to cost with the cheapest option at the left end and the more expensive options in the upper right end. The cost effectiveness spans from CATCH values of about -160 to 200 $[\frac{\$}{ton\ CO_2}]$ using the central estimate.

Abatement measures representing high reduction effect are wider than the ones with low reduction effect. To address the uncertainty of cost and abatement potential, the IMO GHG-study has decided to present ranges rather than single values of the CATCH parameter for each value, which explains the three different estimates.

This MACC computation from the IMO GHG- study is applied to the world fleet as a whole, and as the figure suggests, as much as approximately 250 Million tons of CO_2 from ships is estimated to be abatable in a profitable way (negative cost) using the central estimate.

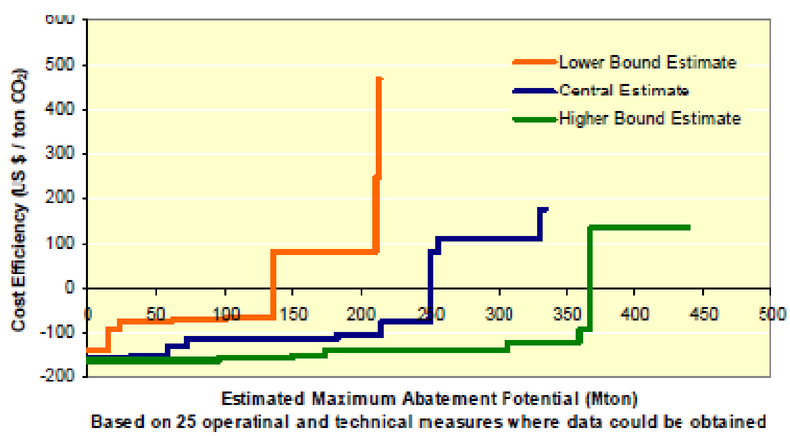


Figure 10: Marginal Abatement Cost Curve for year 2020, fuel price of 500$/ton(IMO GHG study, 2009, #1)

IMO's MACC curve also adopts a social perspective - in other words it answers the question of what it would cost the world economy to reduce emissions by a specific amount targeted towards the year 2020. Despite of this, the IMO GHG study gives little insight to the expenditures that ship operators would have to make in order to achieve a required emission reduction on a specific ship of fleet. This is because the different abatement measures vary so much both in cost and abatement potential regarding the ship type and size. So an aggregated view for the world fleet has little value to a shipowner wanting to evaluate the potential of its specific fleet.

The CATCH parameter utilized to compute a MACC is a helpful tool in addressing the problem of evaluating and selecting abatement measures in shipping. The Marginal Abatement Cost Curve (MACC) could be computed for either a ship, a fleet or aggregated for the whole world fleet like in Figure 10.

However the MACC methodology requires the access to important data about cost and reduction effect related to abatement measures. The industry (here DNV) has an advantage in pursuing with this kind of studies since they have easier access to this kind of information.

A newer version of the MACC in relation to the"Low Carbon Shipping" project has recently been developed by DNV R&I (DNV, 2009, #18). Their MACC's are considering 25 abatement measures and the target is here again aggregated for the world fleet, using 59 ship segments as basis.

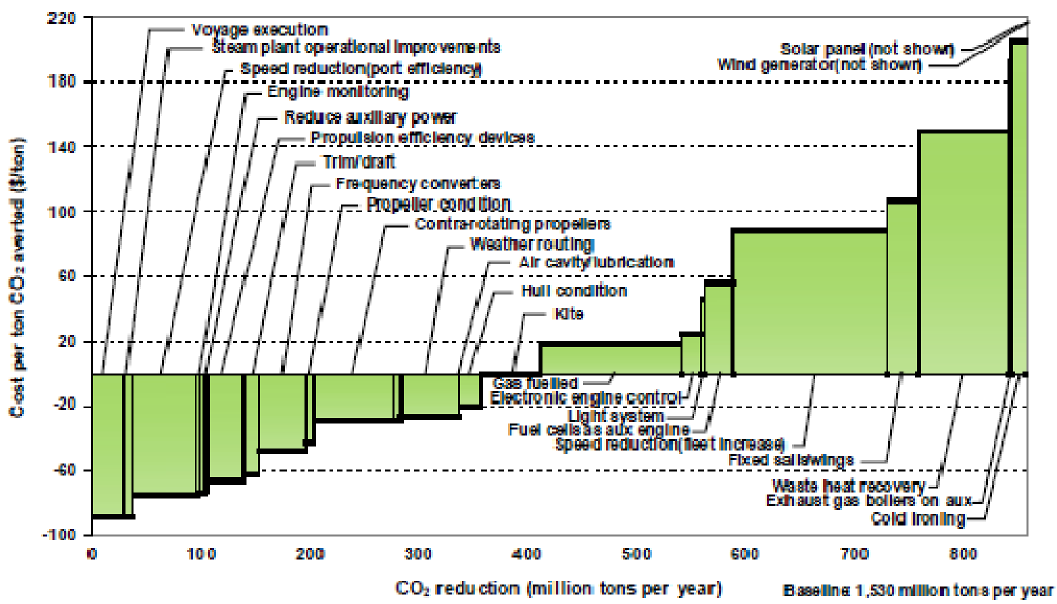


Figure 11: Marginal abatement cost curve for world shipping fleet in 2030. (DNV, 2009, #18)

This figure is quite similar to the MACC curve from the IMO GHG-study but the different abatement measures are more visible and labelled, which makes it easier to see the different measures and their individual reduction effect.

1.2.4 *ECONOMY OF ABATEMENT MEASURES*

This section presents the details of the MACC methodology to assess the cost-effectiveness of abatement measures. In general, abatement measures have two important cost/benefit-properties:

– Lifecycle cost of the measure [$]
– Reduction effect of the measure [tons of CO_2 per lifecycle]

The life cycle cost considerations of GHG emission abatement methods could be divided into these underlying posts:

- Investment cost (Cap Ex) : Cost of implementing the method which is a non-recurring cost. This post implies development and engineering, installation, purchase of parts etc.
- Operating cost (OpEx) : The operational cost is the yearly cost of maintaining a measure in operation. This post includes among other things maintenance, training of crew and purchase of spare parts. It is important that the total operational cost of the measure is aggregated on the lifetime of the abatement measure (or the remaining lifetime of the ships if this is shorter).
- Negative cost related to fuel savings: Most of the measures related to energy efficiency are intended to save fuel cost. This benefit is directly dependent of the actual fuel price which makes this value quite variable with market cycles.
- Opportunity cost related to lost income (downtime of ship or reduction of payload)

The overall life cycle cost of an abatement measure can then be presented as below:

$$\Delta C_i = K_i + S_i + \sum O_i - B_i,$$

Where:

– ΔC_i is the total cost of the measure *i*;
– K_i is the capital cost of the measure *i*, discounted by the interest rate and service years;
– S_i is change in the operational service cost of the measure *i*;
– O_i is the opportunity cost related to lost service time/lost capacity due to the installation of the measure and the discounted costs related to alternative uses of capital.
– B_i is the benefit from saved operating cost (energy savings) from that measure, which is a product of the price of energy and the saving of energy.(Wang and Russell, 2010, #19)

Considering the total amount of CO_2 reduction achieved by a measure during its lifecycle and the overall life cycle cost of the measure during the same period, the price of abating one ton of CO_2 eq. heating will be displayed as the CATCH parameter. (Eide, 2009, #17, Bruce Russell, et al., 2009, #20, Wang; and Russell;, 2010, #21)

$$\text{CATCH} = \frac{\Delta C_i}{\Delta E_i} \text{ in } \left[\frac{\$}{\text{ton } CO_2}\right]$$

Where:

– ΔC_i is the total cost of the technology i aggregated on the technologies lifetime;
– ΔE_i is the expected carbon emission reduction of the measure i aggregated on the technologies lifetime;

2 MULTI CRITERIA DECISION MAKING AS A SYSTEMIZED APPROACH FOR EVALUATING AND SELECTING ABATEMENT MEASURES

This chapter is intended as a brief background on basic Multi Criteria Decision Analysis.

Multi criteria decision analysis is a formal decision aid which is proposed in this paper to illustrate, assist and promote the process of evaluating and selecting abatement strategies targeted towards a specific fleet of vessels.

The decision to reduce carbon emission is not an easy one to make. There are many factors that operators need to consider before choosing which measure to implement, including cost effectiveness, feasibility, performance and compatibility with other ship systems.(Corbett and Chapman, 2006, #22)

The evaluation and selection of abatement measures faces a high degree of uncertainty both regarding cost and utility evaluations. The choice of options may also be affected by differing perspectives, viewpoints and preferences among stakeholders. Some stakeholders may be interested in reducing emissions or keeping low operational complexity while others are restricted to meet economic goals. The use of a formal decision analysis can assist with and clarify the conflicting goals. Key tradeoffs and uncertainties will become more transparent through such a process and thus make the decision more transparent.(Corbett and Chapman, 2006, #22)

As main background literature related to this chapter I used two books dealing with multi criteria decision theory and two decision analysis manuals which had a more applied approach on how to proceed with formal decision analysis.

Books:	Multi Criteria Decision Analysis, An integrated approach (Belton a nd Stewart, 2003, #23, Hwang and Yoon, 1981, #24)
Manuals:	Guidebook to decision-making methods ((IPPC), 2007, #4, Baker, et al., 2001, #25, Department for Communities and Local Government, 2009, #26)Multi-criteria analysis: a manual (Department for Communities and Local Government, 2009, #26)

2.1 WHAT IS MCDM

There are several definitions of Multi Criteria Decision Making. Commonly it is said to be both an approach and a technique to assist with and formalize complex decision making.

Multi Criteria Decision Making (MCDM) is also termed Multi Criteria Decision Analysis (MCDA) or Multi Criteria Decision Aid. It is an integrated approach for exploring decisions and assisting decision making where there are multiple conflicting goals measured in incommensurable units. Typically the methodology is applied where decision making implies analyzing a lot of information of a complex nature - often reflecting different viewpoints which change with time. (Belton and Stewart, 2003, #23).

Multi Criteria Decision Analysis is an aid to decision making, a process which seeks to:

Integrate objective measurement with value judgment
Make explicit and manage subjectivity
(Belton and Stewart, 2003, #23)

2.2 THE MULTIPLE CRITERIA PROBLEM

Most of the literature on MCDA tends to suggest that the typical application of MCDA is a decision problem consisting of choosing the best solution amongst several alternatives. Also by definition, MCDA must involve the consideration of multiple (often conflicting) criteria. A criteria can be defined as “a means or standard of judging”. (Belton and Stewart, 2003, #23)

In the literature, on may notice that there are two sets of problem settings. One problem to be addressed consists of choosing amongst a finite number of already defined solutions. The other problem consists of choosing a solutions without having a defined set to choose amongst (design). These two solutions sets respectively correspond to the two problem-categories : Multiple Criteria Decision Analysis (MCDA) and Multiple Objective Decision Analysis (MODA). MODA is often related to the design phase where one seeks to find a “best” solution amongst infinite possibilities. MCDA is more related to the best choice of already specified finite number of alternatives (Hwang and Yoon, 1981, #24), (Belton and Stewart, 2003, #23).

With this in mind, the decision problem of evaluating and selecting the best abatement measures for a ship or fleet coincides best with the application area of MCDA, since the problem here is considering a finite number of specified abatement alternatives. As such , only MCDA techniques are discussed further in this paper.

For clarity, a few MCDA definitions are needed to describe the typical multi criteria problem:

Decision Maker: The person(s) which have the authority to make the decision.

Facilitator: The multicriteria analysis may be guided by one or more facilitators who assist the decision maker through the decision process.

Alternatives: Different options which are to be evaluated as possible solutions.

Criterion: A measure of value or effectiveness for an alternative.

Attribute: A characteristic that describes, in part, the state of a product or system.

and provides a means of evaluating the levels of an objective.

Objective: An attribute with a direction of desired change.

Constraint: An attribute that has a threshold.

Goal: A value or level of aspiration that is to be achieved, surpassed, or not.

(Hwang and Yoon, 1981, #24)

To exemplify the concept of a typical MCDA problem, one can imagine the personal decision making of choosing a house to buy. There will exist several finite a*lternatives* of houses for sales. For the buyer(*decision maker*) to be satisfied there are also different *criteria* of effectiveness, for example price, location, age and so on. which will affect the buyers level of satisfaction. The criteria could be of either quantitative or qualitative nature.

Attributes may consider the *criteria* to judge the preference for one *alternative* versus another. Each *alternative* house has an *attribute* given for each *criteria*. One house could then have the quantitative *attribute* "100000 $" related to the *criteria* "cost" while the qualitative *attribute* "very good" , is accorded to the *criteria* "location". Natural *attributes* are commonly understood by all stakeholders, and these include cost or physical properties like volume or weight. When natural *attributes* are not available, one can choose to construct an *attribute* which involves assigning a value to describe the effectiveness related to the specific *criteria*. (Corbett and Chapman, 2006, #22)

The *objective* in the decision is the desired direction of change related to each *attribute*: the cost is for example desired to be minimized while the location is to be as rated as qualitatively high as possible.

The example above illustrates a typical multi criteria problem, but MCDA can address different types of problems relatively similar to a personal choice of house. Historically MCDA has been used for a widespread number of contexts. This could include everything from business context, academic context, public context and even governmental or political context.

The different problems where MCDA is applicable are widely diverse. However even with this diversity, all problems are considered to share these following common characteristics:

- Multiple criterion and objectives: An existence of different criteria generated by the decision maker.
- Conflict amongst criteria: For example in minimizing cost one will most likely minimize benefit as well.
- Incommensurable units: Each criteria/attribute is expressed with a unit of measurement either quantitative or qualitative which is not comparable to others. For example the cost is in [$] and the age is in [years] - both quantitative and incommensurable attributes.
- Design or Selection: The solution of the decision problem is either related to a design or a selection of previously specified finite alternatives.

(Hwang and Yoon, 1981, #24).

Belton, lists six different categories of problems for which MCDA may be useful in his book.

1. The choice problematique: simple choice between a set of alternatives.
2. The sorting problematique: sort actions into classes or categories of acceptance.
3. The ranking problematique: To place options in some form of preference ordering.
4. The description problematique: describe actions and their consequence in a formalized and systematic manner, so that decision makers can evaluate these actions.
5. The design problematique: To search for, identify and create new decision alternatives to meet the goals and aspirations revealed through the MCDA process.
6. The portfolio problematique: To choose a subset of alternatives from a larger set of possibilities, taking account not only of the characteristics of the individual alternatives but also of the manner in which they interact with positive and negative synergies.

(Corbett and Chapman, 2006, #22, Belton and Stewart, 2003, #23)

In this paper the decision problem of interest would relate to category nr. 2 or 6, where the desired outcome of the analysis will be to either choose a subset or a ranking of options in some form of preference ordering.

2.3 WHAT CAN MCDA DO?

"Simply stated, the major role of formal analysis is to promote good decision making. Formal analysis is meant to serve as an aid to the decision maker, not as a substitute for him. As a process, it is intended to force hard thinking about the problem area: generation of alternatives, anticipation of future contingencies, examination of dynamic secondary effects and so forth. Furthermore, a good analysis should illuminate controversy – to find out where basic differences exist in values and uncertainties, to facilitate compromise, to increase the level of debate and to undercut rhetoric – in short "to promote decision makin""

(Keeney and Raiffa, 1972, #28)

One of the principal aims of MCDA is to help decision makers organize and synthesize information in a way which makes them feel more confident about making a decision. Other advantages can include making a decision more transparent, providing focus for discussion and structuring the means of a problem. The persons involved in a multi criteria decision analysis will commonly get a better insight to the actual conflicting goals in a decision making process both from their own and from others' perspective. The benefit of learning and sharing information within a group of persons is not to be neglected. However, the concept of an optimum does not exist in a multi criteria framework and it is important to state that the result of the analysis will not necessarily give an objective answer to a problem. Decision makers are not relieved of the responsibility of making difficult judgments. (Belton and Stewart, 2003, #23).

2.4 THE PROCESS OF MCDA

There is a considerable amount of literature on different MCDA techniques, and a wide range of models have been developed to aggregate the information in different ways. However, the process is similar for most cases and can roughly be described by the 7 steps as shown in the figure below:(Department for Communities and Local Government, 2009, #26)

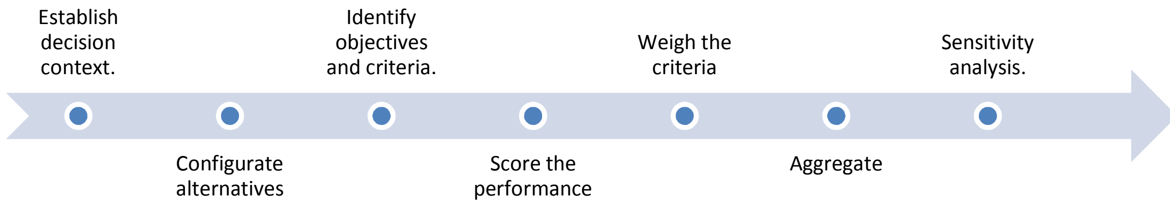


Figure 12: Overview of a typical MCDA process

1. Establishing the decision context: aims of the MCDA, identification of decision makers and other key stakeholders, designing the socio-technical system for conducting the MCDA and considering the context of the appraisal.
2. Configuration of alternatives to be appraised: the starting set.
3. Identification of objectives and criteria: Identify criteria for assessing the consequences of each option and organize the criteria by clustering them under high-level and lower-level objectives in a hierarchy.
4. "Scoring". Assess the expected performance of each option against the criteria and then assess the value associated with the consequences of each option for each criterion. Describe the consequences of the options. Scoring the options on the criteria and checking the consistency of the scores on each criterion.
5. "Weighting". Assigning weights for each of the criterion to reflect their relative importance to decision.
6. Aggregation: Combine the weights and scores for each option to derive an overall value and examine the results. Calculate overall weighted scores at each level in the hierarchy.
7. Sensitivity analysis: Check if other preferences or weights affect the overall ordering of the options.

(Department for Communities and Local Government, 2009, #26)

Each step of this process will be described further in the following paragraphs.

2.4.1 STEP 1: ESTABLISHING THE DECISION CONTEXT.

It is not sure that the aim of the analysis will stay fixed throughout the process. As a consequence of getting thorough insight into the decision problem, new issues may be raised and a signal of change or a shift of aim may occur during the decision process. Still the MCDA has to have a starting point, and a statement of initial aims is crucial to formulating the successive stages. Key factors which will help get through the initiation phase are listed below.

- Identifying objective and aim of the analysis
- Identifying stakeholders
- Identifying conflicting goals
- Identify scope of work
- Identifying the information to be gathered
- Identify timeframe and constraints of the study
- Identifying result goals and the benefit goals of the MCDA
- Identifying the risks and opportunities

These factors raise concerns that are broader than just the aims of the MCDA, but thinking of them will help to provide a context for the analysis which will affect subsequent steps.(Department for Communities and Local Government, 2009, #26)

2.4.2 STEP 2: CONFIGURATION OF ALTERNATIVES AND IDENTIFICATION OF FEASIBLE SOLUTIONS

Since this paper is dealing with predefined solutions (finite number of possible alternatives), the initiation of the MCDA requires an identification of options to be appraised. The *starting set*, in this case abatement measures, consists of the different alternatives to be evaluated, rated and later ranked in the MCDA process. In this study the abatement options are identified from literature reviews, brainstorms, internet searches and in cooperation with the decision maker in the shipping company. The main aim of the first identification is to come up with as many alternative solutions as possible. Key factors to this process are creativity and open-mindedness. Overanalyzing each alternative will not be productive in this phase, and even if an option in reality is not applicable, the option would eventually be screened out later in the process of analyzing the fitness of each alternative. (Department for Communities and Local Government, 2009, #26)

The result of such a brainstorm is a listing of possible alternatives, herein called the *starting set*. Thereafter, many of the these solutions from the starting set may not be applicable since all the options will have requirements which will indicate the feasibility or non-feasibility in the specific study. Figure 13 illustrates this screening process. The essential task here is to segregate the requirements from the criteria. Requirements are used to screen out the inadequate alternatives from further evaluation while criteria are used later to evaluate each alternative (Baker, et al., 2001, #25).

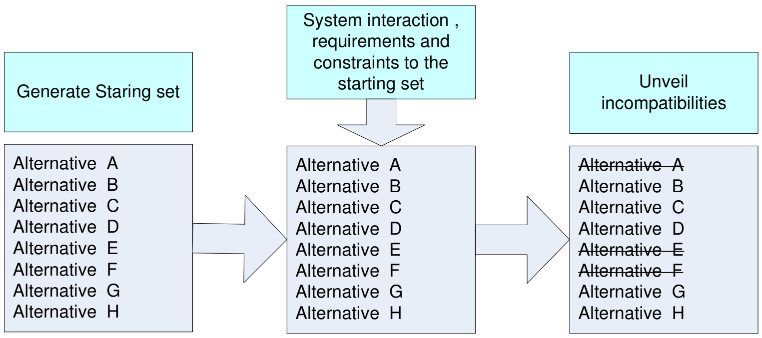


Figure 13: Suggested process to filtrate the starting set from non compatible measures

In all cases, whether the options are given in the initiation phase of the study or have been developed on the way, one should be open to the possibility of modifying or adding to the options as the analysis progresses.

2.4.3 STEP 3: IDENTIFICATION OF OBJECTIVES AND CRITERIA

Objectives and criteria express the many ways that options create value. When options are already given, the 'bottom-up' way to identify objectives is commonly used to ask how the options differ from one another in ways that is of importance. Sometimes the overall objectives are given and sometimes one must agree on them with stakeholders and decision maker prior to the decision process These objectives are further broken down into criteria, some of which are susceptible to numerical measurement, or qualitative evaluations (Department for Communities and Local Government, 2009, #26).

"The true test while segregating requirements and criteria is to ask the question; 'If an otherwise good alternative does not meet this requirement, should it be dismissed or considered?' If he answer is to exclude the alternative, this is truly a requirement. If the answer is to consider the alternative, then this requirement must be changed to an objective or a criteria of success."

(Baker, et al., 2001, #25)

Usually no singular alternative will be the best for all objectives, requiring alternatives to be compared with each other. The best alternative will be the one that is the nearest to achieve all objectives. Each criterion should measure something important, and not depend on another criterion (Department for Communities and Local Government, 2009, #26).

Criteria should be:

- Able to discriminate among the alternatives
- Complete – include all goals
- Operational – meaningful to the decision maker's understanding of the implications of the alternatives
- Non-redundant – avoid double counting
- Few in number – to keep the problem dimensions
- Manageable

(Baker, et al., 2001, #25)

Baker et al. also presents several methods to facilitate criteria selection.

- Brainstorming: Team brainstorming may be used to develop goals and associated criteria.

- Round Robin: Team members are individually asked for their goals and the criteria associated with them. The initial elicitation of ideas should be done non-judgmentally – all ideas are recorded before criticism of any is allowed.

- When members of the goal-setting group differ widely in rank or position, it can be useful to employ the military method in which the lowest ranking member is asked first to avoid being influenced by the opinions of the higher-ranking members.

- Reverse Direction Method: Team members consider available alternatives, identify differences among them, and develop criteria that reflect these differences.

- Previously Defined Criteria: End users, stakeholders, or the decision-maker(s) may provide criteria.

2.4.4 STEP 4: SCORING –EVALUATION OF THE PERFORMANCE

Having identified alternatives, options and criteria, the attributes of each alternative needs to be scored. Scoring is the process of assessing the performance of an alternative against a specific criteria. The most common methods to score this performance are ranking techniques, pair wise comparison techniques or simply direct rating of alternatives.

Direct rating is used in this paper. This method of scoring was chosen for its ease of set up and implementation. A ranking of the different alternatives will not give a good insight to the relative performance and a pair wise comparison is too time consuming. Since it is planned to include ship operators into the scoring-process, it was favourable to use an easily understandable method when rating the performance. The relative judgments by direct scoring are often regarded as easier for people to make than absolute judgments.

Furthermore, it is chosen to use direct linear value scales for each criteria and the qualitative criteria are scored by direct rating. Direct rating can be viewed as the construction of a value scale where one defines only the end points of the scale. Since it is a local scale, the alternative which performs best according to the specific criteria is given the highest score of 100 points. The alternative which performs the worst is given a score of 0 points. All the other alternatives are positioned directly on the scale to reflect their performance relative to the two reference points.

To be able to score a performance, a value scale is needed, and to construct such a scale it is necessary to define two reference points, maximum and minimum score. These two reference points need to be allocated with numerical values to each end point. If the criteria has a natural attribute (like $) the end points are often chosen to be the maximum and minimum values in the scale. However in the case of a constructed attribute these value points have to be constructed indirectly and commonly they are assigned values such as 0 and 100 or 0 and 10. A value scale can also be constructed using qualitative “proxys” like “good”, “neutral” etc.

(Department for Communities and Local Government, 2009, #26)

2.4.5 *STEP 5: WEIGHTING*

Weighting criteria is basically the same thing as asking the question " What is more important for you in choosing an abatement alternative?" Furthermore, weighting the criteria must allow a location of all the criteria in some kind of relative importance.

There are, like for the scoring process, different techniques for weighting criteria. Pair wise comparison, ranking or direct rating are the most common. The weighting of each criteria is in this study also performed by direct rating, called "The Swing Weights Method". This method is based on giving direct scores to each criteria between 0 and 100 points.

To weight the first criteria, the decision maker is asked to imagine an alternative where all the criteria are on their worst consequence level. The decision maker is then asked to point out the criteria which he would most preferably change from its worst to its best level. This criteria is regarded of highest importance and rated with a score of 100 points. The decision maker is then asked to look at the remaining criteria and again points out the criteria he next would ameliorate from worst to best performance. Relatively to the previous criteria, the decision maker will again give a score (lower than 100 points) to this second criteria. This procedure is repeated until all the criteria have been attributed a score between 0 and 100 point. The scores are then normalized and given a percentage of importance as illustrated in the figure below.

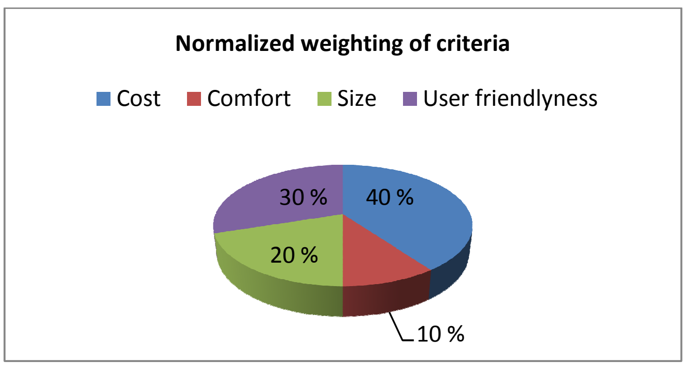


Figure 14:Example of preference weight of criteria

The advantage of this method is that it reflects well the evaluators judgments on relative criteria importance. (Baker, et al., 2001, #25)

2.4.6 STEP 6: AGGREGATION AND RESULTS

Next in the process comes the aggregation of all the evaluations, which is not an easy task considering the aggregation of incommensurate values. The way of dealing with this is simply to normalize the different scorings into values between 0 and 100 and weight the scores according to the criteria. This task is done by computers, letting the preference score for option "i" on criterion "j" be represented by " s_{ij}" and the weight for each criterion by "w_j"; In other words, multiply an option's score on a criterion by the importance weight of the criterion, do so for all the "m" criteria, and sum the products to give the overall preference score for each alternative. Then repeat the process for the remaining alternatives.

$$S(s_{ij}, w_j) = \sum_{j=1}^{m} s_{ij}, w_j \rightarrow final\ aggregated\ score\ between\ 0\ and\ 100\ \%\ for\ alternative\ i$$

2.4.7 STEP 7: SENSITIVITY ANALYSIS

A sensitivity analysis should be carried out to investigate how the preliminary results and conclusion of the decision model are sensitive to small changes in the input data. The technical perspective of a sensitivity analysis is the objective examination of the effect on the output of a model of change in the input. Furthermore a sensitivity analysis can provide basis to test intuition and understanding of the problem, and in the group context, the function is to allow the exploration of different perspectives on the problem. In this case, the input in question may be value functions, scores and criteria-weights. The overall purpose of the sensitivity analysis is to validate the evaluation results by demonstrating that small changes in input values do not change the final ranking (Baker, et al., 2001, #25) (Belton, 2003 #31).

In this study two types of sensitivity analysis will be performed to check the robustness of the final ranking.

- Sensitivity of weightings : Since weightings are often the subject of more disagreement than scores (Department for Communities and Local Government, 2009, #26), a sensitivity analysis is conducted to find out if other preferences and weightings affect the final ranking of the options.
- Sensitivity of fuel price: Since the fuel price is regarded as the most important parameter in relation the cost-effectiveness of the different abatement options, an investigation is made to see how the MACC curve will be affected by changes in market fuel prices.

3 CASE STUDY: USING MACC AND MCDA METHODOLOGY TO RANK ABATEMENT MEASURES

This chapter applies the MACC and the MCDA methodology to evaluate and rank a set of abatement measures. The aim of the case study is to suggest a priority list of emission abatement strategies to implement on the Grieg fleet. The seven previously described steps of a typical MCDA process will now be used in a real case scenario of a realistic decision problem.

Figure 15: Overview of the typical MCDA process

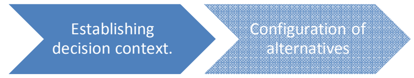
3.1 EXPECTED RESULTS

The goal of this case study is to explore the possibility to use a formal decision aid in the process of evaluating and selecting GHG abatement measures to specific fleet. The expected results of this case study are:

- An identification of relevant abatement measures to implement on Grieg ships.
- A priority utility ranking of these measures according to chosen qualitative criteria beyond cost effectiveness.
- A priority cost-effectiveness ranking of these measures using the MACC-methodology developed by DNV R&I.
- An aggregated marginal cost and utility plot .
- An identification of the main obstacles for the implementation of cost effective abatement measures.

As for my own expectations as a student, I wish to understand how a vessel owner or operator decides which abatement measures to implement first, and when to employ these measures. Revealing factors preventing ship owners from installing cost efficient measures is also something I find particularly interesting.

3.2 ESTABLISHING DECISION CONTEXT



This step establishes the context of a hypothetical decision problem of evaluating and selecting abatement measures to the fleet of Grieg Shipping Group.

Grieg Shipping Group operates a fleet of 27 ships in total . The standard ship is an open hatch bulk carrier of ca. 47.000 DWT. The company's vessels are categorized in 9 groups of sister ships where the oldest (A-class) are from 1985 and the newest (K-class) are built in 2009-2010. The cargo is mainly wood pulp, rolled paper and other forestry products but the ships also carry a wide range of other unitized cargoes, project cargoes and containers. The main deck is equipped with gantry cranes to load and unload the box shaped holds.

The Open Hatch trade is based on long term contracts and strong relationships where high quality, efficiency, punctuality and flexibility are necessary to ensure customer satisfaction in the long run.(Grieg, #29)

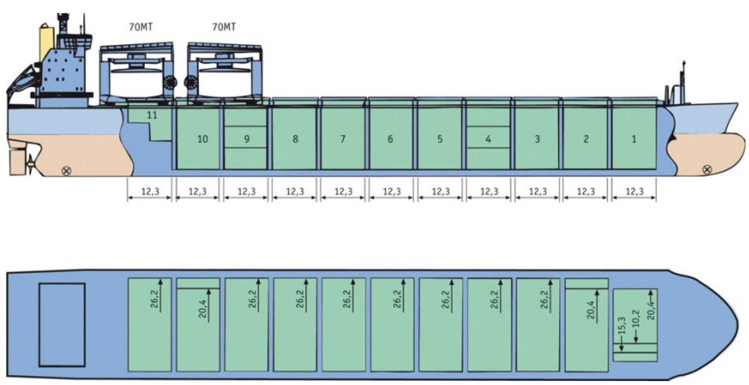


Figure 16: System model of the ship "Star Istind"

Grieg Shipping Group as a company is known for keeping a high environmental profile and they wish to go beyond regulations to reduce their Green House Gas emissions and comply with their own internal environmental policy. The GHG-reduction plan is then allocated to the company's Project Department who are made *Decision Makers* in selecting and implementing emission abatement measures.

Given the number of alternative abatement options to choose amongst and the different properties involved for each abatement option, it was decided to make use of a MCDA technique in prioritizing the different abatement options. The objective is to facilitate a clear and constructive discussion between the project department and the board in coming up with a priority list of abatement measures to implement . Table 3, on next page, is a systemized scheme of the identified problem context:

Table 3: Overview of the actual decision problem context

Problem	Identify a priority list of abatement measures for the reduction of carbon emissions from the Grieg ships
People involved	Operation managers, superintendent, project engineers, crew, ship management, QA-department, purchase dept., board.
Context	Project EMISOL, Project Low Carbon Shipping
Time	Limited, project duration 6 months with possibility for email and phone communication. One week at shipowner's office
What is specified as Result goals	A ranking of preferred abatement measures and a presentation of barriers for implementation
What is specified as Benefit goals	Raising awareness and knowledge of abatement measures to reduce GHG-emissions both towards decision makers and participants in the study.
Identification of alternatives	Brainstorm, discussion, internet searches and finally limited by the cost data availability
Identification of criteria	Identified by student and Senior Project Engineer together
Score performance	Subjective scores, directly rated by participants, cost data estimation provided by DNV
Weighting of criteria	Swing rankings made by participants
Process evaluation	Survey, interviews or written responses, observation

3.3 Configuration of alternatives

The identification of possible abatement measures to implement, is the second step in the MCDA process. The key question while processing this step is to ask "What can be done to reduce GHG emissions from the ships?" There are a variety of possible solutions to reduce carbon emission and different methods to identify them. In this study, however abatement options are identified from literature reviews, brainstorms, internet searches and in cooperation with the decision maker in the shipping company. The result of the brainstorms is a listing of possible alternatives to evaluate further, herein called *starting set*.

Literature used as source to identify the options are:

- (IMO GHG study, 2009, #1)
- (Melanie Hobson, et al., 2007, #16)
- (Crist, 2009, #14)
- (Eide, 2009, #17)
- (DNV, 2009, #18)

Since the different papers seldom are consistent in their choice of abatement options, it was not easy to screen out *a starting set* of alternatives for the case study. The IMO GHG study illustrates as much as 49 technical and operational measures to reduce carbon emissions, while the other papers tend to look at 8-15 measures individually. Furthermore, not all stakeholders are consistent in how they define a measure. A measure called "improvement of voyage execution" could be seen as a single measure in one setting, while being divided into 3 different methods called "weather routing", "fuel consumption monitoring" and "trim optimization" in another setting. Therefore, to identify the actual content related to each measure was not an easy task.

However, the framework developed by the IMO GHG-study from Figure 17 was used to map possible abatement measures and screen out the redundant options.

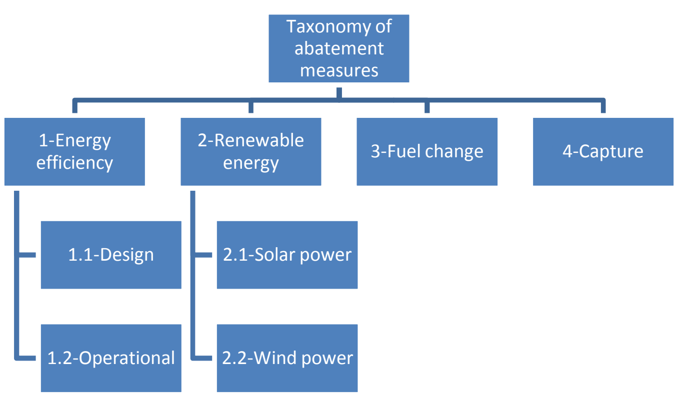


Figure 17: Categorization of abatement measures (IMO GHG study, 2009, #1)

Within the framework from Figure 17, several abatement measures can be identified. Questions I asked myself in choosing the alternatives to include in a starting set was:

What is the impact to the system from each measure?
Are the measures physically compatible with the actual ship?
Are there any measures which are already installed onboard this ship?
If yes, do these measures exclude other measures from the starting set?
Are the measures physically compatible with each other and could they be aggregated?

In choosing the option to include in the starting set I encountered an important constraint in the lack of potential reliable cost and abatement data. As the two most important characteristics of abatement measures are the cost and the abatement benefit of the measure, I found myself forced to exclude measures where this information was missing. How much will a measure reduce and how much will it cost? These are the essential questions, and which measures to include in my study were limited by the access to this information.

Measures where available cost data was accessible - with the help from DNV R&I - were then used to construct the initial starting set prior to the evaluations. The starting set is presented in Table 4.

Table 4: Listing of the starting set of CO2abatement alternatives

	Measure	main engine	aux engine
1	Voyage execution: Refers to the potential improvement of the voyage execution in means of speed and fuel consumption of main engine	X	
2	Speed reduction(port efficiency): Increase the loading and offloading efficiency in port ,shorter time in port means slower speed in voyage.	X	
3	Speed reduction(fleet increase): Reduce speed of voyage by increasing the total cargo capacity in nr of ves	X	
4	Engine monitoring: Closer monitoring of the engines condition, maintain optimal engine load	X	
5	Reduce auxiliary power by ensuring optimal load on auxiliary engines.		X
6	Propulsion efficiency devices: Propeller boss cap fins, ducts, vans etc.	X	
7	Trim/draft: Trim optimization of the ship during voyage.	X	
8	Frequency converters		X
9	Propeller condition: Increase propeller polishing to optimal	X	
10	Contra rotating propeller: installation of new propeller of type contra rotating	X	
11	Weather Routing: Better decision support to the crew with recommendation of the most optimal route based on forecasted weather and currents	X	
12	Air cavity lubrication: Decrease the hulls frictional resistance trough lubricating the hull with air	X	
13	Hull condition: Maintain optimal hull friction by using anti fouling paint and optimum hull cleanings	X	
14	Electronic engine control: is a type of electronic control unit that determines the amount of fuel, ignition timing and other parameters an internal combustion engine needs to keep running	X	
15	Light system: Reduce lighting and energy consumers onboard ship.		X
16	Waste heat recovery: Adding turbosystem to recover the exhaust gas energy	X	
17	Exhaust gas boilers: use engine waste exhaust heat to get warm water		X
18	Cold ironing		X
19	Solar panels		X
20	Wind generator: Decrease the main engine load by using wind generators as bi-propulsion power		X
21	Kite: Decrease the engine load by using kite as bi-propulsion power	X	
22	Fixed sails: Decrease the main engine load by using fixed sails as bi-propulsion power	X	
23	Gas fuelled	X	
24	Fuel cell aux engine		X
25	Steam plant	X	

All the measures included in the chosen starting set belong to the two overlying subgroups of abatement measures:

- 1-Improvement of energy efficiency
- 2-Use of renewable energy

The next idea was to adapt the starting set of abatement measures to the actual the Grieg ship type. The measures identified by DNV was given on a general ship segment basis and all measures herein are not necessarily compatible on the Grieg ships. A way of filtering out the non-feasible solutions was to look at each measure separately and find the requirements and system interactions of each measure.

Every measure will have specific requirements related to implementation. The abatement measure of" Kite" will for example require a specific amount of area and strength on the ship deck to make the installation possible. In the same manner, an improvement of the "Weather Routing" requires that the ship in question operates under strong currents and weather conditions for the abatement potential to reach its initial abatement goal. The process of unveiling incompatibilities between abatement measures and the actual ship is shown in Figure 18.

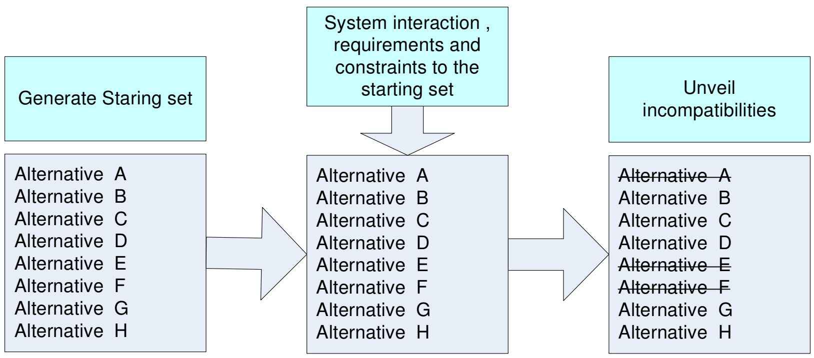


Figure 18: Representation of a screening process

Based on the described procedure of unveiling requirements, three of the methods were erased due to incompatibility:

Table 5: table Identifying requirements to each abatement measures

Measure to reduce main engine emissions		Applicable to specific ship type
1	Voyage execution	Yes
2	Speed reduction(fleet increase)	Yes
3	Speed reduction (port efficiency	Yes
4	Engine monitoring	Yes
6	Propulsion efficiency devices	Yes
7	Trim/draft	Yes
9	Propeller condition	Yes
10	Contra rotating propeller	Yes
11	Weather Routing	Yes
12	Air cavity lubrication	Yes
13	Hull contition	Yes
14	Electronic engine control	Yes
16	Waste heat recovery	Yes
21	Kite	Yes
22	Fixed sails	Yes
23	Gas fuelled	to complex
25	steam plant	Not actual to ship type
Measure to reduce auxilliary emissions		
5	Reduce auxilliary power	Yes
8	Frequency converters	Yes
15	Light system	Yes
17	Exhaust gas boilers	Yes
18	Cold ironing	Depending on port facilities
19	Solar panels	Yes
20	Wind generator	Yes
24	Fuel cell aux engine	Not applicable before 2015

It should be mentioned that Grieg Shipping Group has already implemented several of the actual abatement measures on different ships in their fleet.

Concerning the feasibility, compatibility and requirements of applying abatement measures, an average ship in the Grieg fleet was used as reference. When ship specific data was needed, characteristics from Star Istind, was used. However the case study is not ship specific and when questioning the compatibility issues of each measures, the Grieg fleet was considered as a whole. The reason for this is partially that I seek an evaluation of all relevant abatement measures and partially that I did not have the opportunity to thoroughly analyze the details of each ship. If this paper had focused on one particular ship, for example Star Istind, the measures could have been more specific to the requirements of each abatement alternative and of course more precise to that specific ship.

3.3.1 Compatibility effects

Furthermore, to investigate the aggregated effect of implementing several measures together, a compatibility investigation was performed. Initially, measures have been aggregated using a simple summarization of reduction effects. A multiplicative aggregation however like shown below is considered as more appropriate in aggregating reduction effects, as they are given in percentage.

$$P_{1+2} = (P_1 + (100 - P_1) \cdot P_2$$

Where:

- $P_2 \text{and } P_2 \text{ are the abatement potential in percentage of respectively abatement measures } 1 \text{ and } 2$
- $P_{1+2} \text{ is the aggregated abatement potential of installing } P_1 \text{ and } P_2$

Furthermore, the aggregated effect of applying measures together may not necessarily be as simple as the calculation shown above. Some measure, especially those which are situated in the same abatement group(Figure 8, p13) may have more complicated aggregation effects.

The methodology to investigate this question is done by computing compatibility matrixes, (Figure 19) one for the main engine reduction and another for the auxiliary engine reduction. These matrixes are supposing that methods from the two different engine don't affect each other since they are acting on different fuel consummators. As shown in the matrix below, the aggregation of measures in green are supposed to have an aggregated abatement effect like shown in the equation above while the effect of aggregating methods in red should be investigated further.

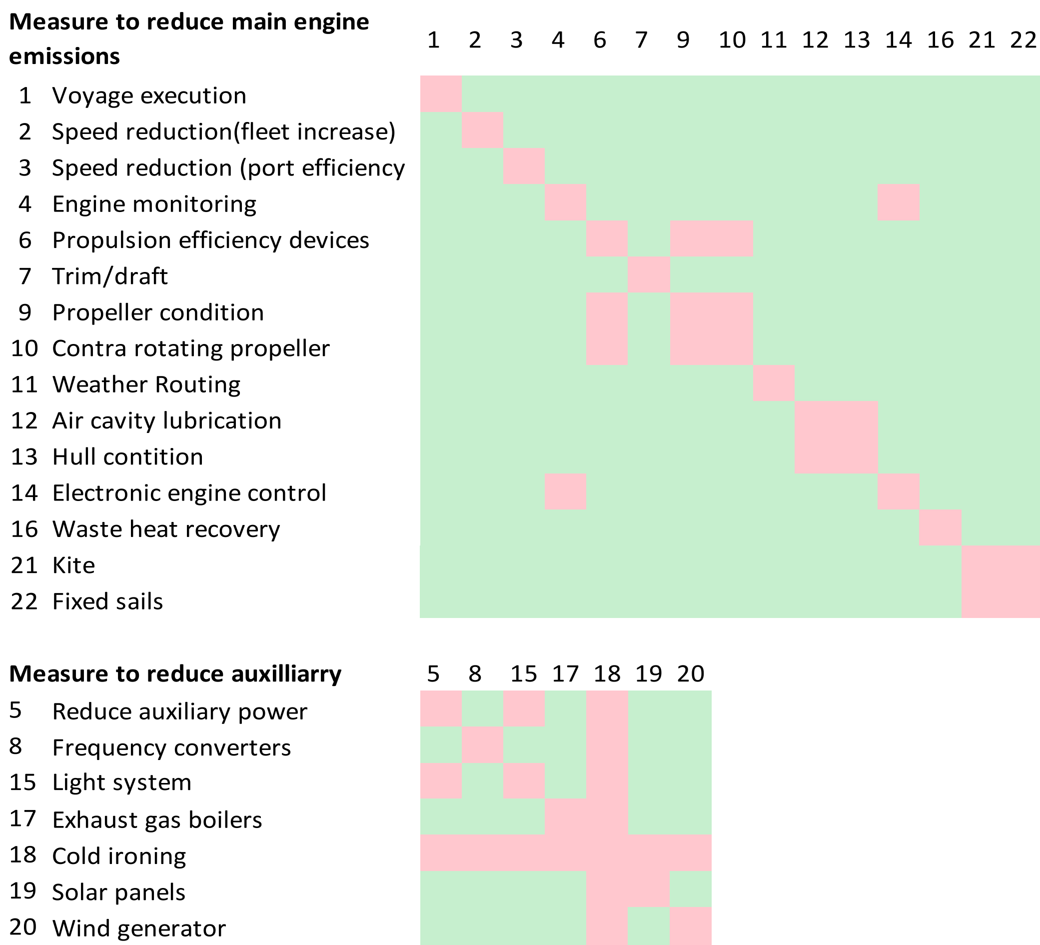
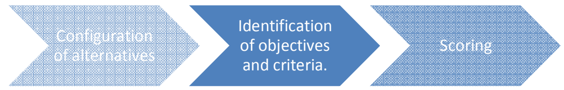


Figure 19: Compatibility matrixes for measure related to main and auxiliary engine.

3.4 Identification of objectives and criteria.



The next step in the decision model is to identify the key criteria which will form the basis of the evaluation. The ship operator's choice of abatement methods could be dependent on many factors, but even if the cost is often highly prioritized, it does not necessarily mean it is the only criteria.

'"Contrary to business school doctrine, 'maximizing shareholder wealth' or 'profit maximization' has not been the dominant driving force or primary objective through the history of the visionary companies. Visionary companies pursue a cluster of objectives, of which making money is only one – and not necessarily the primary one. Yes, they seek profits, but they're equally guided by a core ideology – core values and sense of purpose beyond just making money" (Baker, et al., 2001, #25)

Below is a systemized scheme of factors related to the performance assessment of an abatement measure.

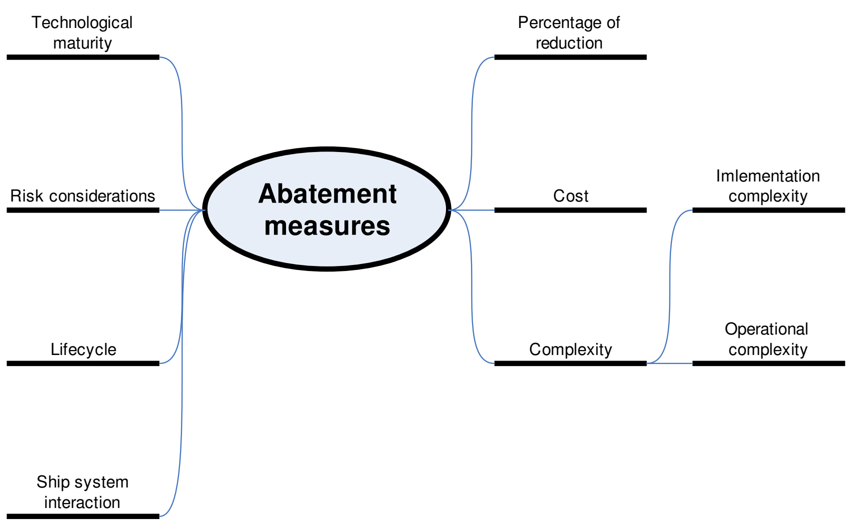


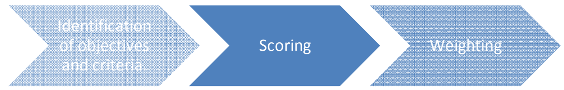
Figure 20:: Systemized scheme of factors which related to the performance of an abatement measure.

To identify which criteria to use in my case study I had to investigate and discuss the wanted objectives of the stakeholders. The key task was to decide what properties were related to a good abatement measure. Commonly, an abatement measure is supposed to reduce the CO_2 emissions, preferably in a cost-effective and easy way. However I wanted to find out more about how other factors can affect a shipowners' choice of abatement measures. Further criteria like risk assessment, technology readiness level and complexity of implementation tend to be areas of interest while comparing the different possible abatement strategies. The job of the criteria is to discriminate between the alternatives and together with the senior engineer in the Project Department I agreed on the following final criteria related to an evaluation of abatement measures.

Table 6: Overview of main identified objectives

Crietria name	Objective	Description	Attribute as unit of measurement	Value scale	Data source
Cost effectiveness	Minimizing cost of measure:	Relates to the amount of money spend on a measures both investment and operational cost	CATCH value in [$/ton CO_2]	Linear from max. to min. value	DNV R&I
Risk	Minimizing general risks	This criteria considers the degradation of the safety onboard for crew, ship and cargo	Qualitative constructed attribute (proxy)	Constructed value scale spanding from 0 to 100 points where 0 corresponds to high risk and 100 to low	Survey at shipowners
Technical maturity	Maximizing technological maturity	Refers to the technology's readiness level, this criteria could affect the ability to get skilled crew, service and assistance. The overall uncertainty about cost and potential could also relate to the maturity of the	Qualitative constructed attribute (proxy)	Constructed value scale spanding from 0 to 100 points where 0 corresponds to low maturity and 100 points to high maturity level	Survey at shipowners
Complexity of implementation	Minimize complexity of implementation	This criteria is an indicator to the complexity related to the implementation of a measure. Processes included in implementation are project management, purchase, installation	Qualitative constructed attribute (proxy)	Constructed value scale spanding from 0 to 100 points where 0 corresponds to high complexity and 100 low coomplexity	Survey at shipowners
Complexity of operation	Minimize complexity of operation	This criteria is an indicator to the complexity related to operation of a measure. Processes included are daily operational procedures which could increase workload to crew, shore personnel and maintenance activities	Qualitative constructed attribute (proxy)	Constructed value scale spanding from 0 to 100 points where 0 corresponds to high complexity and 100 low coomplexity	Survey at shipowners

3.5 SCORING



Once criteria have been identified, the alternative abatement meas ures can be rated accordingly to each criterion of effectiveness.

3.5.1 SCORING OF QUALITATIVE CRITERIA: TECHNICAL MATURITY, RISK AND COMPLEXITY

To proceed this scoring I used employees from the Grieg shipping company as participants in a survey. I needed participants with expertise, knowledge and experience in ship operation, and since I already knew the company from a previous internship, It felt natural to include them in my study. The survey was conducted in Grieg's offices in Bergen where I held and introduction before sending out surveys to each participant. The survey was carried out individually with the possibility to ask question and get help from me during the process. In all 8 employees participated in the survey.

- 3 Superintendents
- 3 Senior engineers from the Project Department
- Operations Manager COO
- Purchasing manager

For each criteria I asked the participants to rate the highest score of 100 points to the alternative which performs best according to the specific criteria, and give 0 points to the alternative which performs worst. All the other alternatives were positioned directly on the scale to reflect their performance relative to the two reference points.

Below is the result of the average scores for each alternative according to the 4 qualitative criteria.

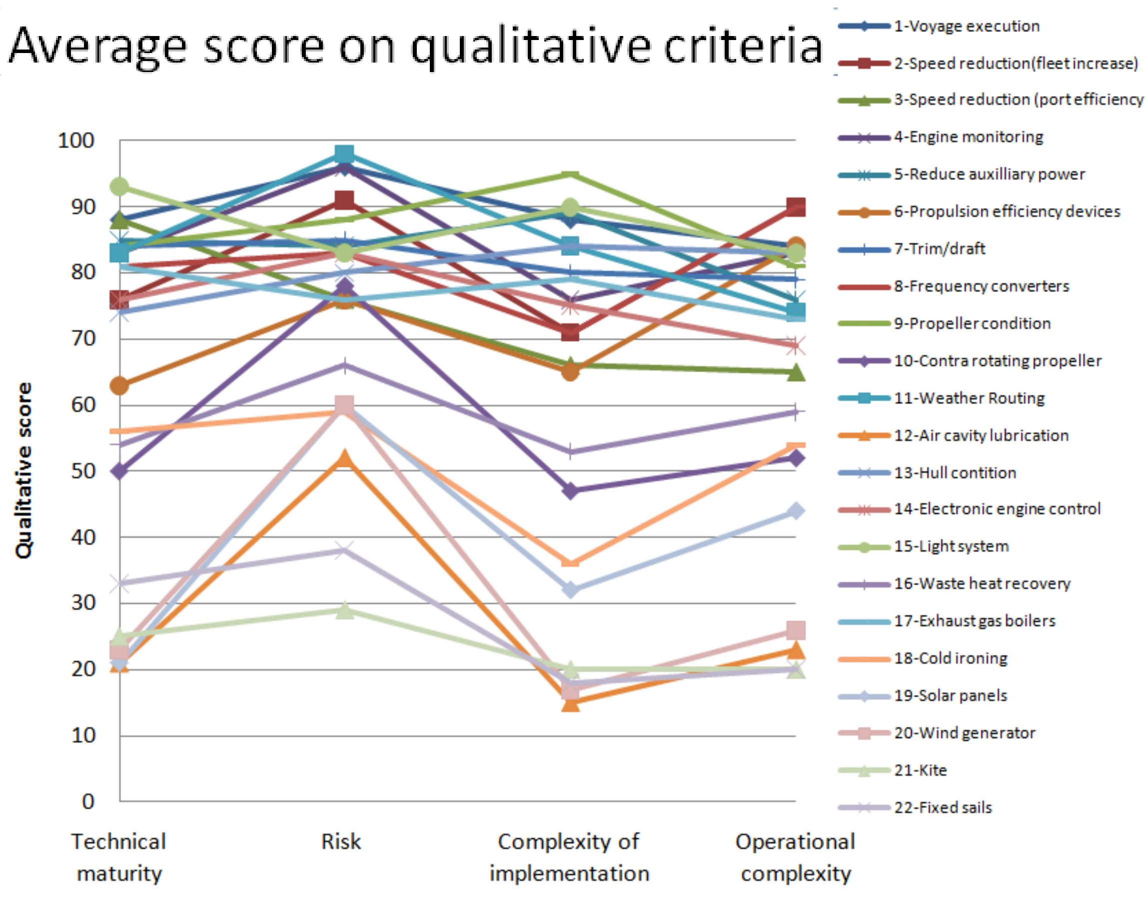


Figure 21: Overview of the average qualitative scores of the alternatives.

3.5.2 SCORING OF QUANTITATIVE CRITERIA: ASSESSMENT OF COST EFFECTIVENESS USING MACC-METHODOLOGY

The criteria of cost effectiveness is much easier to rate since it is quantitative in nature and does not rely on subjective opinions. My source of information related to data on the cost and reduction effect of each abatement option is DNV R&I(Eide, 2010, #27). The data has been compiled by DNV and used for analysis on world fleet level, as presented by DNV in the Pathways" study (DNV, 2009, #18), and documented by Eide et al. (Eide, et al., 2010, #30). The data received is applicable to a "standard ship in the segment Bulker 35000-59999 DWT" and thus not necessarily accurate for a specific open hatch bulker of the Grieg fleet. However in the context of my study I regard these estimations as quite appropriate to the Grieg ships. It must be stated that these data should be considered as first estimates and that DNV does not take responsibility for the use of these data in this context.

The methodology chosen to calculate and present the cost effectiveness and benefit of the different abatement options is the Marginal Abatement Cost methodology developed by DNV R&I as discussed earlier in part 1.2.4

The resulting MACC-curve plotted for the Grieg fleet is shown below. The calculations are based on a net present value approach over the average ship age of 15 years, interest rate of 8% and a fuel price of 475 $/ton. Additional assumptions are shown in appendix 9.1.

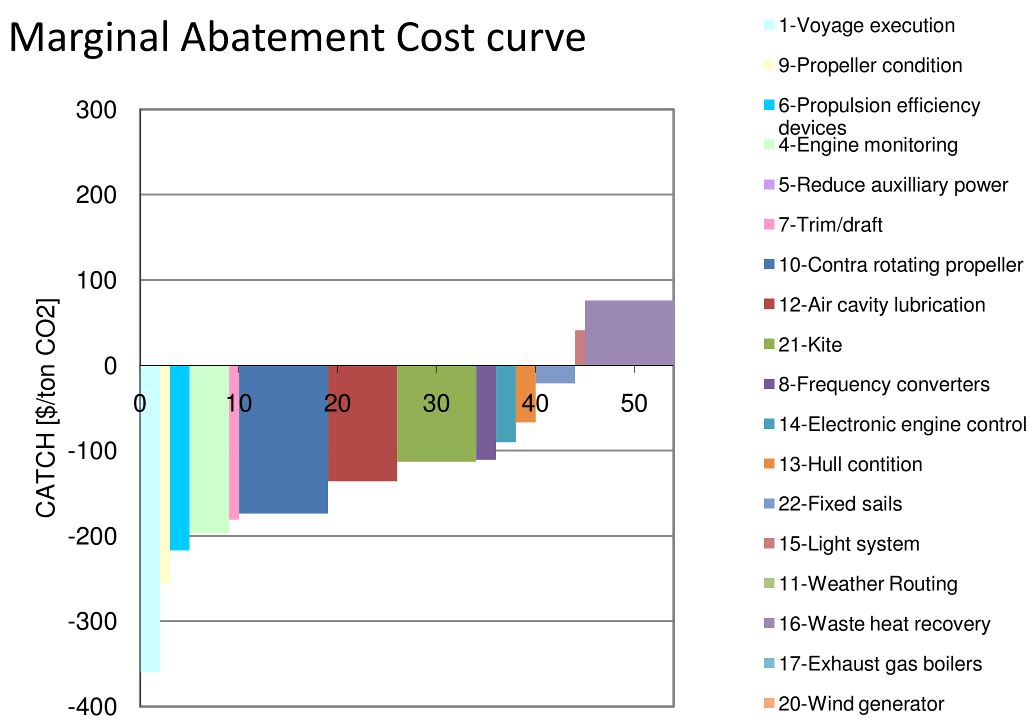


Figure 22: Marginal Abatement Cost curve for the Grieg fleet, plotted with given estimation-data from DNV R&I.

As seen on Figure 22, and according to the calculations of the CATCH values, as much as 44% of this ship's GHG emissions could be abated cost effectively by additional aggregation and without considerations to compatibility effects.

3.6 WEIGHTING OF CRITERIA: QUANTIFYING THE IMPORTANCE OF EACH CRITERION:

The purpose of this step is to decide the relative importance of the different criteria and find out which criteria that are preferred by the ship operator. The criteria here are weighted similarly to the scoring of performance by direct rating. Grieg employees were asked to express their order of preference by giving the scores of importance (0-100 points)to each criteria. The preferred criterion was given a score of 100 points and the next best was then scored with relative importance accordingly to the first. The result of the criteria-scoring is shown below.

Table 7: Weighting of criteria

Weighting of criteria	Cost	Technical maturity	Risk	Complexity of implementation	Operational complexity
	80	100	100	60	90
	50	80	100	50	90
	80	60	100	60	60
	50	100	90	50	80
	50		100	25	25
	80	80	100	60	90
	60	60	100	50	80
	80	100	95	70	90
Average weighting	**66**	**83**	**98**	**53**	**76**

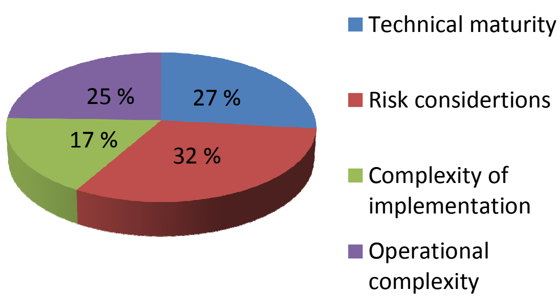


Figure 23: Result of the swing weights of the qualitative criteria (excluding cost)

As we see from Figure 23, the importance of minimizing the risk to crew, ship and cargo is highly valued by the participants of the survey. 6 out of 8 participants chose this criteria as the preferred criteria related to a choice of GHG emission abatement measure. In second place they chose the criteria of technical maturity.

3.7 AGGREGATION

In bringing all the scores together, I have chosen to segregate the qualitative utility scores from the cost effectiveness estimations due to the difficulty of transforming the cost evaluations into normalized values between 0 and 100. The aggregation was then continued only for the qualitative criteria. These aggregated scores , representing the overall utility rating are shown in Figure 24. Aggregation of scores was completed using a simple summarization of the different weighted scores like show in the equation below:

$$S(s_{ij}, w_j) = \sum_{j=1}^{m} s_{ij} \cdot w_j$$

-final aggregated score between 0 and 100 for alternative i considering m numbers of criteria

Below is the result of the aggregated qualitative utility scores for each alternative. The preferred solution is "1-Voyage execution" and has the highest score whereas the least preferred criteria "21-Kite" has the lowest score.

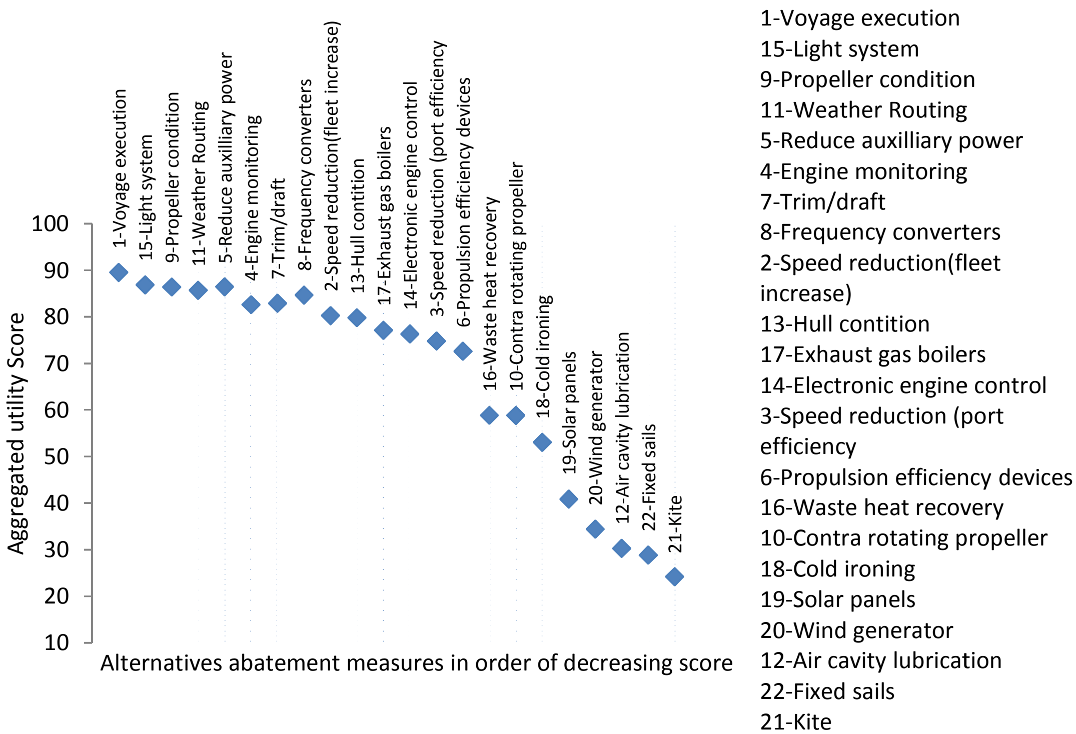
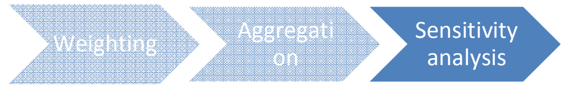


Figure 24: Final aggregated utility score to all alternatives.

3.8 SENSITIVITY ANALYSIS



As discussed in chapter 2.4.7, sensitivity analyses can be useful to the decision makers by allowing them to evaluate the outcome of the decision model and make sure the ranking of alternatives is robust for small changes in input data.

3.8.1 SENSITIVITY OF WEIGHTED PREFERENCE

The first sensitivity analysis which will be performed is a check of the weight and preference distribution. The following figures will show how an increase in criterion weight could change the outcome.

The following sensitivity graphs were produced by the commercially available software HIVIEW. The plots shows how the final aggregated score would differ as we change the weight of one specific criteria from 0 % importance to 100%. In the figures, the initial assigned weight of criteria is presented as a vertical red line. There are 4 sensitivity plots, and each of them represents the fluctuations of changing weights on one specific criterion.

In general, if the plot of an alternative is primarily horizontal along the graph, the option could be seen as a robust option. The alternatives represented by a diagonal line in the plots would be more sensitive to a change in criteria weight. The overall final score of such an option could be much affected by the weighting.

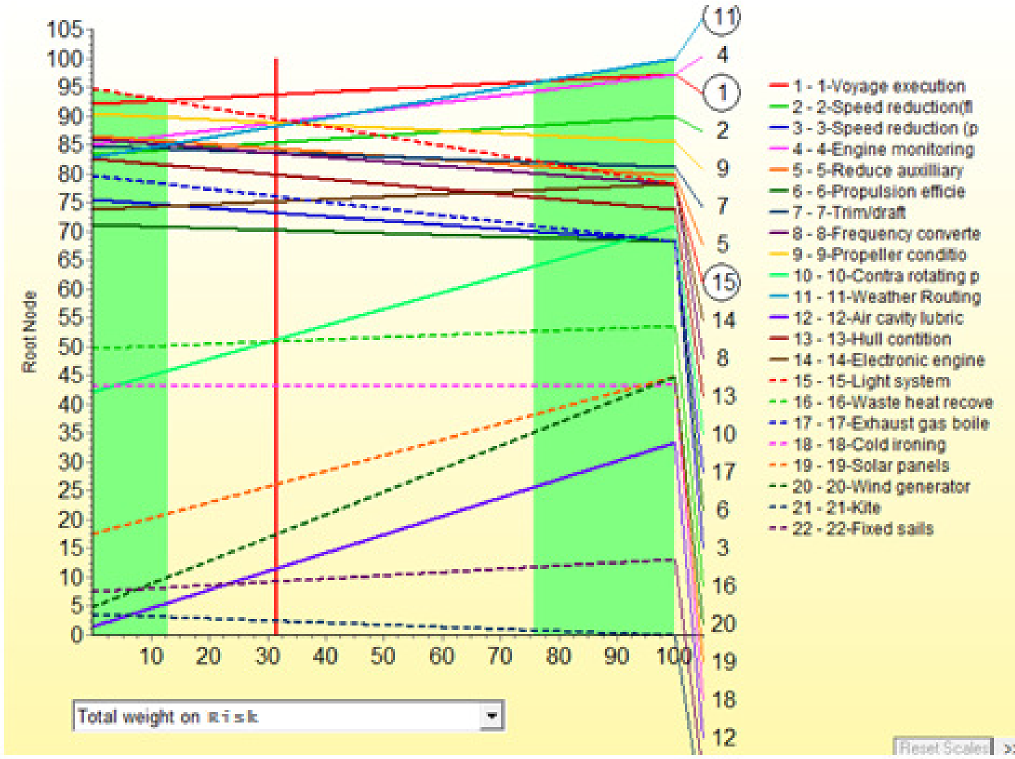


Figure 25: Weight sensitivity of the criterion of Risk considerations

Increasing the weight of the criteria “Risk” from the current value of 32% to a higher importance of 76 % would result in “11-Weather routing” having the highest overall utility score. The initially best solution of “1-Voyage execution” would step down as second best solution. If the criteria weight is decreased to the value of 12% the option of “15 Light system” climbs up as the best solution.

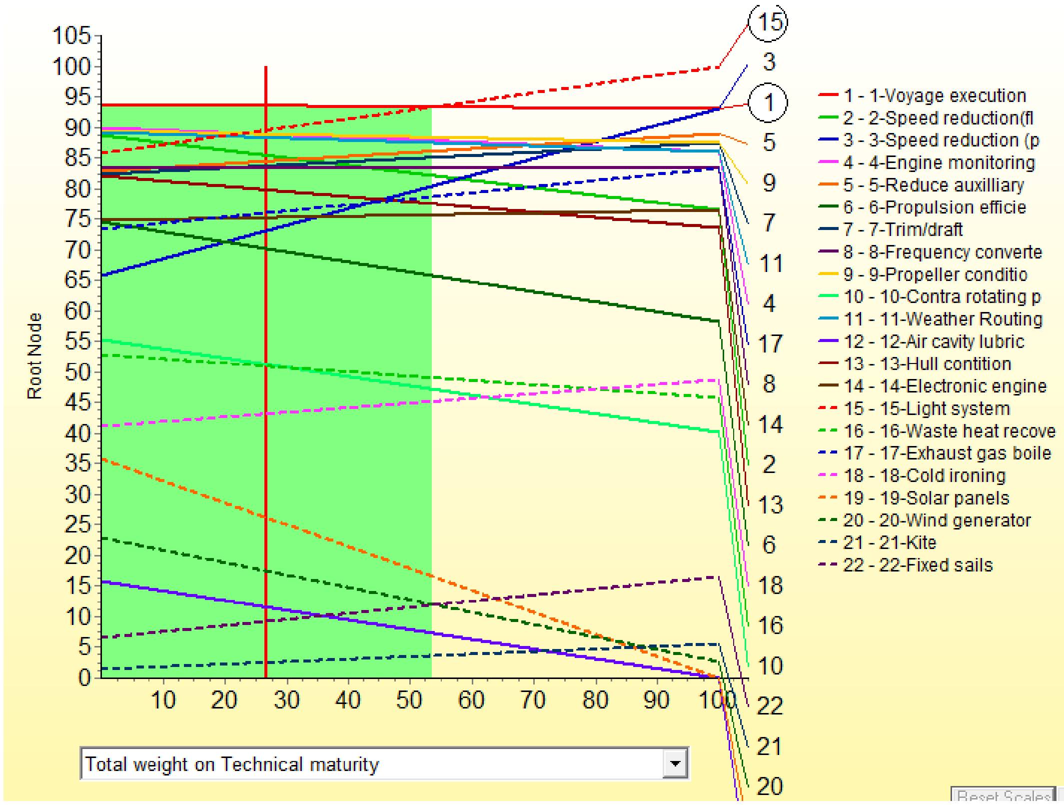


Figure 26: Weight sensitivity of the criterion Technical maturity

Increasing the weight of "Technical maturity" from the current value of 27% to 54 % would result in "15 Light system" to top the utility score listing. The initial winner of " 1-Voyage execution" would step down as second best option.

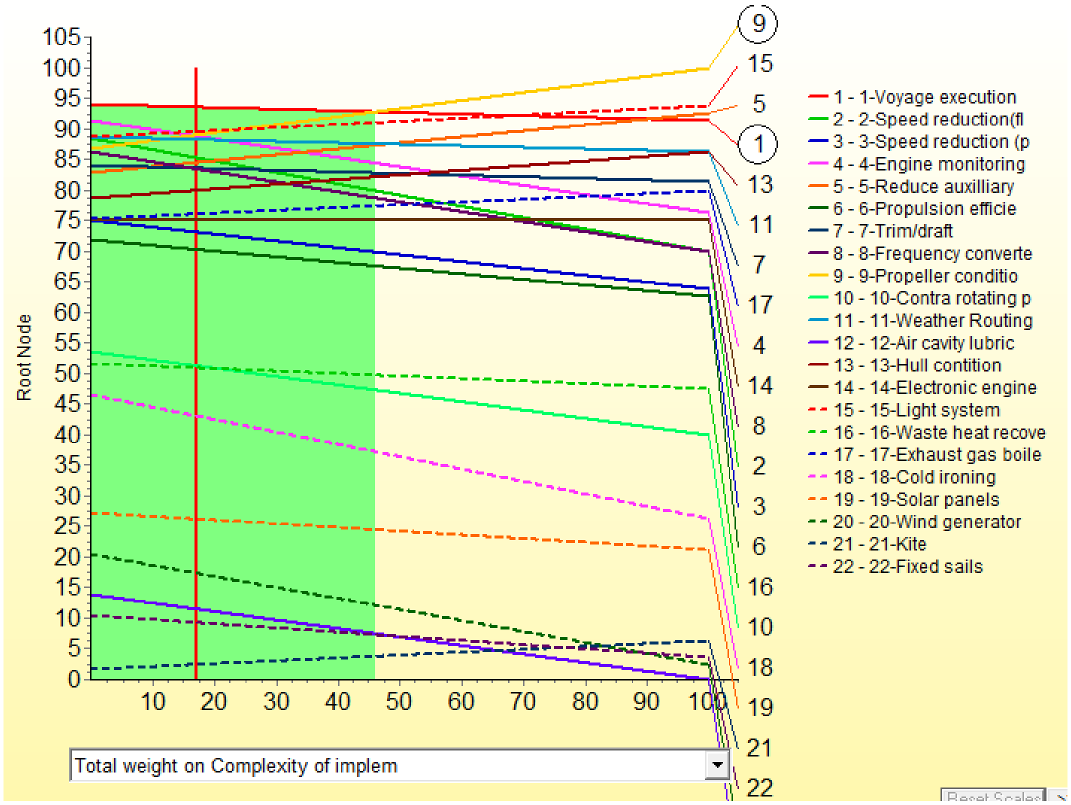


Figure 27: Weight sensitivity of the criterion of complexity of implementation

Increasing the weight of Complexity of implementation from the current value of 17% to 46 % would result in “Propeller condition” having the highest overall utility.

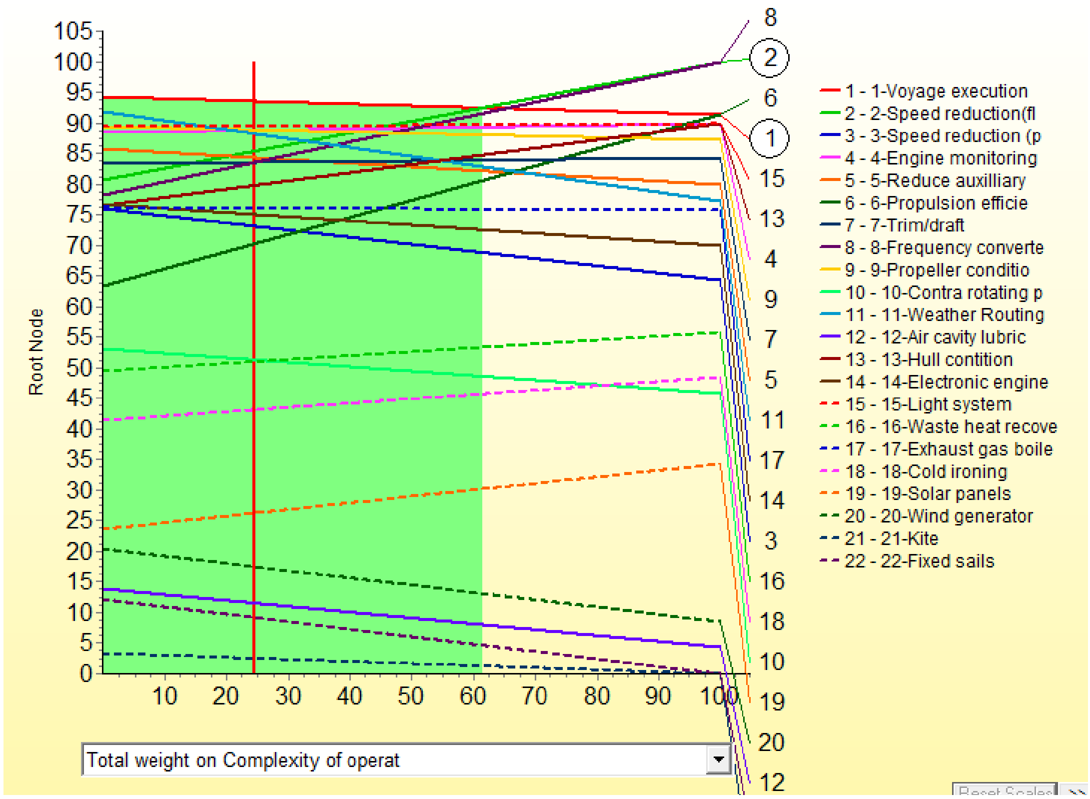


Figure 28: Weight sensitivity of the criterion of Complexity of operation

Increasing the weight of "Complexity of operation" from the current value of 24,5% to 61 % would result in "Speed reduction by fleet increase" having the highest overall utility score. It also seems like the option "Frequency converters" quickly climbs upwards as the preference of the criteria of "Operational complexity" increases.

As the software summary in Figure 29 shows, all changes downwards or upwards in criteria preference have to exeed 15 % from the current weight to change the output ranking sequence: From this we can conclude that the sensitivity of weighting is quite low.

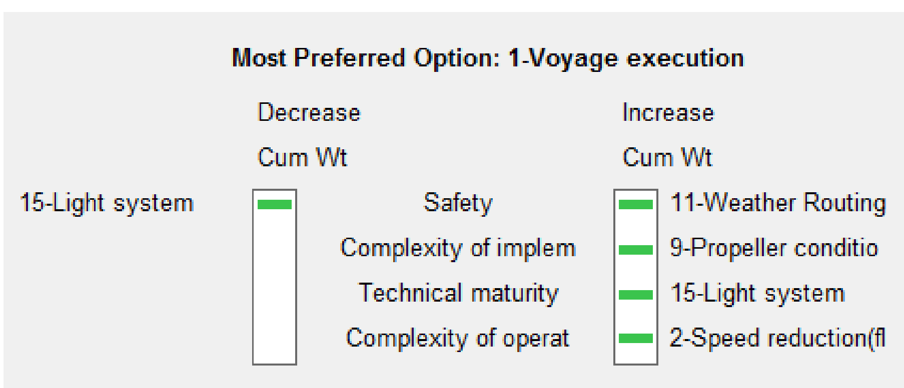


Figure 29: Overview of output changes by changing the prefference weights

3.8.2 SENSITIVITY OF FUEL COST

To gain a deeper insight into how the cost effectiveness of the measures vary with market fuel price fluctuations, the MAC-curves have been plotted for different fuel costs. A pessimistic scenario with a fuel price of 200$ and an optimistic scenario with a fuel price of 600 $ per ton has been investigated. The results of the new MAC's are shown below. Obviously, as shown in Figure 31, an increase in fuel price to 600 $ would increase the cost effectiveness for each and all abatement measures.

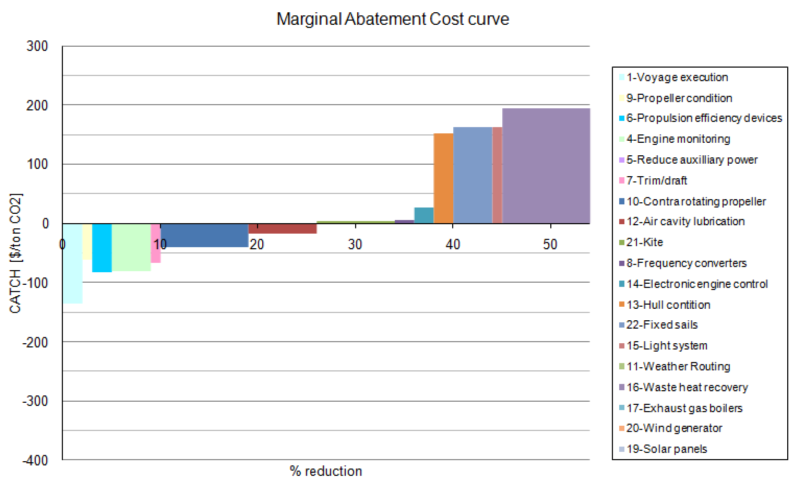


Figure 30: Overview of MACC with a fuel price of 200 $/ton

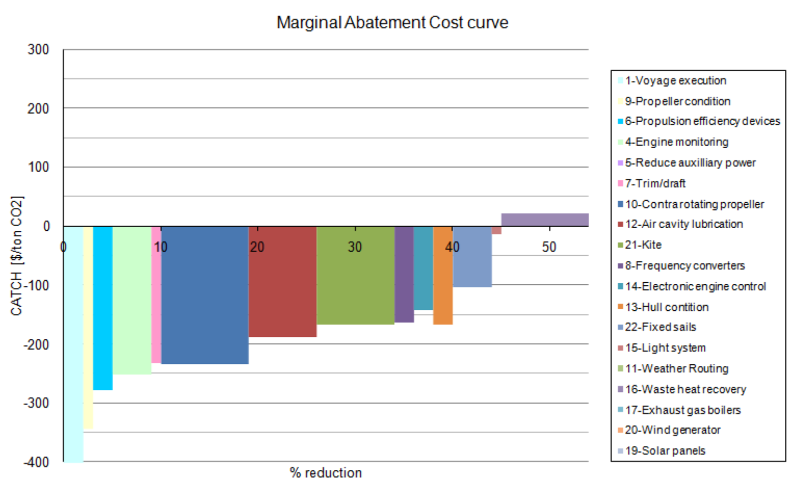


Figure 31: Overview of MACC with a fuel price of 600 $/ton

4 IDENTIFICATION OF MAIN BARRIERS

Abatement options have the potential to play an important role in reducing the overall GHG emission from shipping. Although economically viable for several applications, they have not fully realized their potential due to several obstacles for implementation in the shipping industry. An investigation has been carried out parallel to the MCDA case study to identify these barriers to GHG abatement measures and suggest ways to overcome them.

The main source of information related to the identification of barriers is the survey carried out at Grieg Shipping Group, combined with different papers and books addressing the matters of barriers to cost effective investments. In this context, a barrier is defined as a mechanism which inhibits a decision or behaviour that appears to be both energy efficient and economically efficient. In particular, barriers are claimed to prevent investment in cost effective energy efficient technologies(Sorell;, et al., 2004, #31).

The concept of "barrier" or "market barrier" was initially investigated by researchers who used economic engineering models to study the technical and economic potential for energy efficiency. They observed that investments with high rates of return were being neglected by the industry and this made them state that such investment were being inhibited by various barriers.

While some barriers act on a general basis as they prevent implementation of any kind of abatement measure, others are specific to one or several abatement measures.

4.1 TAXONOMY OF GENERAL BARRIERS

Sorell et al. present a taxonomy of general barriers to energy efficiency. This taxonomy includes risk, imperfect information, hidden costs, access to capital, split incentives and bounded rationality. A description of each barrier category is presented in Table 8 (Sorell;, et al., 2004, #31)

Barrier	Claim
Risk	The short paybacks required for energy efficiency investments may represent a rational response to risk. This could be because such investments represent a higher technical or financial risk than other types of investment, or that business and market uncertainty encourages short time horizons.
Imperfect information	Lack of information on energy efficiency opportunities may lead to cost effective opportunities being missed. In some cases, imperfect information may lead to inefficient products driving efficient products out of the market.
Hidden costs	Engineering-economic analyses may fail to account for either the reduction in utility associated with energy efficient technologies, or the additional costs associated with them. As a consequence, the studies may overestimate energy efficiency potential. Examples of hidden costs include overhead costs for management, disruptions to production, staff replacement and training, and the costs associated with gathering, analysing and applying information.
Access to capital	If an organisation has insufficient capital through internal funds, and has difficulty raising additional funds through borrowing or share issues, energy efficient investments may be prevented from going ahead. Investment could also be inhibited by internal capital budgeting procedures, investment appraisal rules and the short-term incentives of energy management staff.
Split incentives	Energy efficiency opportunities are likely to be foregone if actors cannot appropriate the benefits of the investment. For example, if individual departments within an organisation are not accountable for their energy use they will have no incentive to improve energy efficiency.
Bounded rationality	Owing to constraints on time, attention, and the ability to process information, individuals do not make decisions in the manner assumed in economic models. As a consequence, they may neglect energy efficiency opportunities, even when given good information and appropriate incentives.

Table 8: Taxonomy of barriers to energy efficiency.

According to Sorell et al. barriers to energy efficiency could be seen in relation to three perspectives: orthodox economics, transaction cost economics and behavioural economics. Considering this, an identification of barriers to energy efficiency would warrant a profound investigation of economic theory, and that is beyond the scope of this paper.

However some main concepts have been used to attempt to and unveil the main barriers at Grieg Shipping Group. During the implementation of the MCDA, some questions regarding barriers to energy efficiency were inserted in the survey.

4.2 RESULTS OF SURVEY AT GRIEG SHIPPING GROUP

During my case study, I tried to identify the most common barriers to implementation of cost effective abatement measures at Grieg Shipping Group. The participants in the survey were asked to mention the main factors which they thought were acting as barriers to the implementation of measures. Their open answers to this question are shown in the table below:

Table 9: Open answers to unveil barriers in implementing cost effective abatement measures

Answers:
Insufficient focus on leadership and long term perspective, insufficient features in the organization and insufficient training of crew
International rules and regulations, getting crew to commit and finding skilled employees to participate in projects.
Safety considerations and cost
Safety considerations
Safety of crew and ship will always have highest priority - always over cost effectiveness. Barriers which could prevent implementation are access to human resources internally and externally to the organization, documentation of cost effectiveness (much of the documentation is based on test environments and has not been implemented on full scale projects). Feasibility, the possibility to carry out different projects simultaneously, training of crew and other users and complexity of implementation onboard.
One barrier is to quantify the abatement potential enough and weighing this against cost. Considering the emerging abatement measures, there is a barrier in rationalizing for the cost. The input given to the decision makers will here be a significant barrier. Furthermore, even if the measures show up to be cost effective, the actual liquidity would represent a factor for every large investment. The lack of rules and regulations which require implementions reduce incentives for leadership and management to implement new technology, even if it is cost effective. Finally, the technology itself is a factor. The technology itself will not function without considerations to training, processes and mangement.

Furthermore, as an attempt to categorize the different barriers, the participants were asked to state, based on the part of the organization they belonged to, which factors they regarded as the most difficult to overcome. Below is an overview of the answers given by the participants.

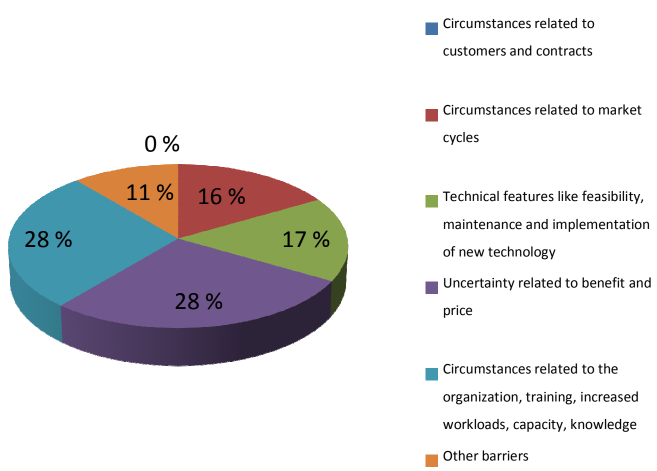


Figure 32: Result of survey- identifying barriers in implementing cost effective abatement measures.

As observed in Figure 32 the circumstances related to the organization, and the uncertainty about pricing and benefit of abatement measures dominate. Circumstances related to customer relationship were not been chosen by any of the participants.

Circumstances related to organization and market cycles were emphasized by superintendents while uncertainty on cost and abatement potential was deemed hardest to overcome by the project engineers.

Some common barriers to energy efficiency are discussed below and an attempt to relate them to the measures of the starting set is made.

Sensitivity to capital expenditure

The ship owner or operator may not have finance or liquidity available to refit their vessels at the time being. This could cause ship operators to choose an abatement measure with low investment cost even if the total lifecycle cost of the measure is higher than another option with a higher starting investment. This factor may prevent cost efficient options with high investment costs from being implemented even if they significantly reduce subsequent the running cost in long run.

Measures from the starting set with high capital cost are listed below:

- 21-Kite
- 19-Solar panel
- 17-Waste heat
- 13-Air Cavity lubrication
- 11-Contra rotating propeller
- 22-Fixed sails or wings

Standardized vessel configuration

If a shipowner wants to have the opportunity to sell a vessel before the intended lifetime has passed, it is often an advantage to have a standardized ship configuration. A standardized configuration means a more flexible ship which is usable for several purposes in contrast to being designed for a particular route, cargo, speed etc. Implementation of abatement methods can come in conflict with these requirements for standardized specification. To exemplify, some measure which affects the overall ship configuration in a significant way are described next:

Due to extensive refitting in the hull shape, the measure of air hull lubrication significantly changes the standard ship configuration. Changes in the propulsion system could also be regarded as a deviation from a standard ship configuration.

Market cycle

The shipping market is characterized by high and low bounds. Especially the low bounds could have an impact on the uptake of abatement measures. The lower bound of the cycle is represented by hard competition where extra capacity is forced out of the market and the aim is to squeeze out the competitors by pushing prices down. This could affect decision makers by leading them to adopt a more careful stance regarding investments. One could suppose that ship owners would be more willing to save fuel cost and speed reduction measures could plausibly be attractive during this lower bound. On the other hand there is little room for taking unnecessary risks and investments in such difficult times.

The peak of the market cycle is characterized by increased demand and freight rates. To maximize profit, ships may operate at full speed and new building orders increase. A steep rise in freight demand, as the high bound of the market cycle would suggest, could cause a high demand of new vessels to deal with the increased trade. Some will say that the quicker a ship owner gets new ships, the quicker he gets return on the investment, thus time spent on development and implementation of abatement measures may be viewed as a loss of valuable time (Crist, 2009, #14).

In busy times however, the order books of ship yards may be full and the only berths left could reach three of four years of waiting time. In this case, there may be enough time to proceed with redesigns, but this may be given a lower priority due to the increased freight activity.

(Stopford, 2009, #32)

A small priority among others.

Emission reduction goals and other requirements can meet in conflicting dilemmas. A ship owning company has many priorities to make and it is not always easy to make all of them match. They may prefer to prioritize safety requirements over environmental considerations and if any conflicts appear, the ship owner will automatically choose to reduce the risk. Operators have to take care of the employees, hold a high safety standard, be a flexible supplier of the transported goods, be on time, have low operational cost, have good customer relationships, and the list goes on. There are many regulations to comply with - especially regarding the safety of cargo and crew, and considering this it is not surprising that environmental measures are not always given highest priority.

(Crist, 2009, #14, Melanie Hobson, et al., 2007, #16)

Uncertainty of cost and benefit

Decision makers tend to lack adequate information about abatement measure costs and reduction potential, and in some cases are not even aware of their existence. This leads them to make decisions based on provisional and uncertain information and consequently to under-invest in energy efficiency.(Sorell, et al., 2004, #33)

Hidden costs

- Much of the uncertainty related to cost and benefit of abatement measures are connected with the idea that several hidden costs exist which are not conventionally included within the engineering-economic models. Sorell et al. present an empirical perspective where the components of hidden costs are divided in three main categories:
- General overhead cost of energy management
  - Cost of employing specialists (energy managers, ++)
  - Cost of energy information systems
  - Cost of energy auditing
- Cost involved in individual technology decisions
  - Cost of identifying opportunities, detailed engineering and design, formal investment appraisal.
  - Cost of formal procedures for seeking approval of capital expenditure
  - Cost of specifications and tendering for capital works to manufacturers and contractors
  - Additional staff cost for maintenance
  - Cost of replacement, early retirement, retraining of staff
  - Cost of disruptions and inconvenience
- Loss of utility associated with energy efficient choices
  - Problems with safety, working conditions, service quality
  - Extra maintenance, lower reliability

Other barriers could include:

- Route specific restrictions
- Cargo specific restrictions
- Speed requirements from contract with customer.
- Lack of class approval rules of new technology.

5 RESULTS AND DISCUSSION

This part of the study discusses two main topics; the output and the validity of the decision model results from the case study (chapter 3) as well as the question of whether or not MCDA has a potential for use in evaluating and selecting abatement measures in shipping.

5.1 INTERPRETATION OF THE DECISION MODEL RESULTS

The decision analysis yields two distinct priority rankings for the problem of evaluating and selecting abatement measures:

- A qualitative priority ranking describing the utility of each abatement alternative based on the employees preferred criteria rating.
- A marginal abatement cost-effectiveness rating based on cost-effectiveness and reduction effect estimations by DNV R&I.

Interpreting the result of these evaluations together should give some insight to both the benefit and the cost-effectiveness of the evaluated abatement alternatives.

5.1.1 EVALUATION OF THE UTILITY RANKING

Figure 33 shows the average qualitative utility scoring results. The scores reflect the relative performance of each alternative according to the four identified utility criteria as perceived by the Grieg employees. Note that a high score for the "risk" criteria indicates that the employee has confidence in this criteria and perceives it as having high performance, and thus somewhat unintuitively – to have an associated low risk. The same applies for complexity. The scores are widespread, and span from the high score of 98 points given to the "Risk" criteria on measure "1-Voyage execution" to a value of 15 points given to the "Complexity of implementation" for "Air cavity lubrication".

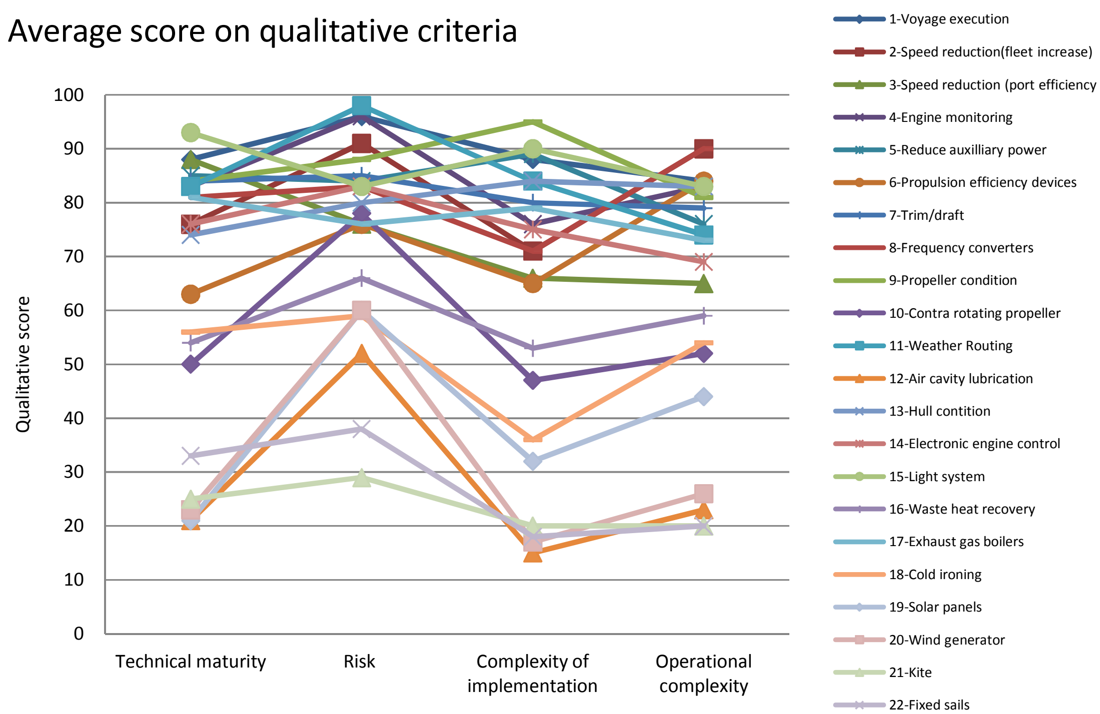


Figure 33: Results of the qualitative utility scoring

Interestingly, none of the measures score very high on one specific criteria and very low on another. The trend is that highly ranked criteria are rated with high scores for all 4 criteria whereas poorly rated measures get low scores for each criteria. The only two measure which seemingly differ a bit on this is the measure of "3-speed reduction by port efficiency" where technical maturity and risk is rated a good deal higher than "complexity of implementation and operation" and "20-wind generator" which has a good "risk" performance compared to the other criteria ratings.

This overall trend could suggest that the criteria are somewhat dependent and that they should have been organized differently.

That being said, it is also important to keep in mind that the identification of criteria could have been significantly improved in the qualitative assessment. The choice of criteria was done by myself in cooperation with the senior engineer in the project department, but after the study I realized that this could have been done significantly better by the Grieg employees. Instead of suggesting the four defined criteria, I could have questioned the group and found out what criteria they deem most important for abatement measures. Other relevant criteria were discussed briefly; The ability a measure has to reduce other emission types like SO_x and NO_x could have been included as a criterion. The actual GHG-reduction effect of each measure itself was also subject for discussion when choosing criteria to include in the decision model.

The aggregated and weighted utility-scores of the qualitative evaluations can be summed up in a figure called Marginal Abatement Utility Curve (MAUC) as shown below. The different abatement measures from the starting set are here presented as columns. The varying width of the columns represents the varying reduction effect of each alternative and height represents the utility score as preferred by the Grieg employees. The goal in this chart is to obtain measures high up on the qualitative score scale and preferably as wide as possible to enhance the reduction effect.

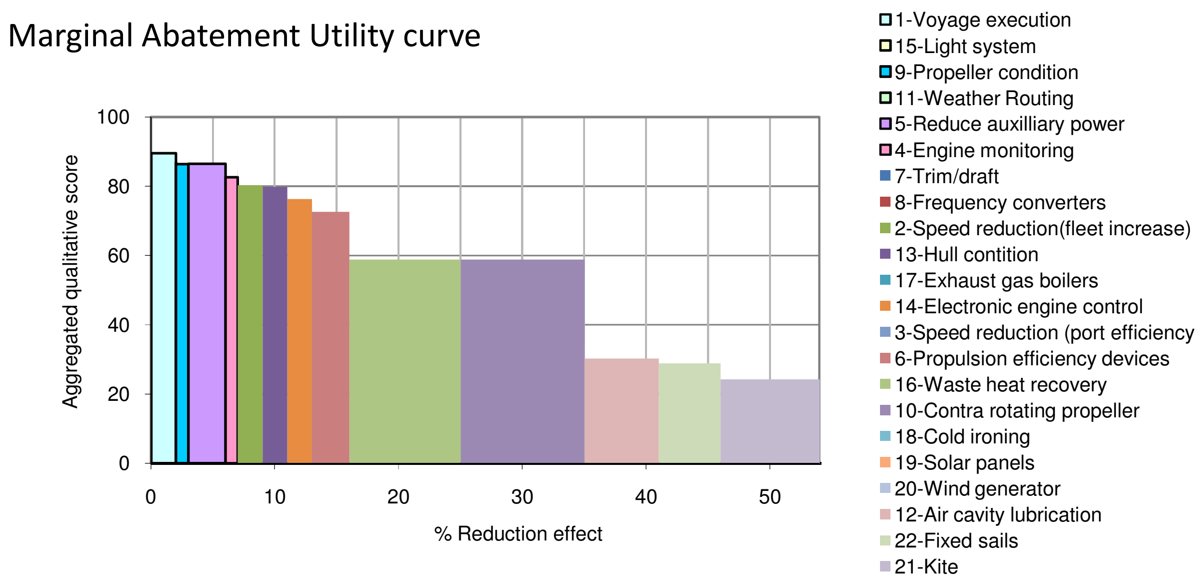


Figure 34: Marginal abatement utility curve as result of the qualitative evaluations (note that some abatement measures does not show as the width (reduction effect) is to small

According to the figure,(see also Figure 24), the abatement measure rated with highest utility score is "1-Voyage execution" followed closely by "15-Light system" and "9-Propeller condition". It could be supposed that all these measures are more or less referring to improvements of ongoing ship operation procedures. The technology and procedures for achieving emission reduction using these kind of measures are known and therefore they could be regarded as better than the rest by the participants of the survey.

On the other end we find the more emerging abatement measures related to the group of renewable energy like "21-Kite" and "22-Fixed sails" or a"12-air cavity lubrication". These are seemingly the least preferred options in means of utility.

The sensitivity analysis showed that the resulting aggregated scores were quite robust in relation to the weighting. This means that the participants had to change any of the initial criteria-weighting by 15% for this to affect the final score sequence (see Figure 23). This shows that small changes in preference of criteria would not affect the overall qualitative ranking.

I wouldn't say that the results of the decision model are very surprising in themselves. As seen in the figure there is a gap between the "known/common measures" and the more emerging and innovative solutions which are still on an experimental level. Note also that the higher rated measures have a relatively low reduction effect compared to the lower rated ones. This is unfortunate, as a measure with both a high qualitative rating as well as high abatement potential would be an obviously preferred choice, depending on cost – which is included in the discussion in the next graph. It is my belief that removing uncertainties and improving information and documentation regarding the emerging measures would improve their qualitative ratings, thus moving the thicker columns to the left, and making the alternatives with the most abatement potential more viable.

It is also interesting to observe the relative scores between the different options. The last three measures have been distributed a score of around a third of the highest rated options, something which gives us an idea of the perceived qualitative differences between the measures.

Within this context it still remains difficult to analyze the value of the results when the scoring is based on a constructed value scale from 0 to 100 points. The scorings are in this way affected by subjective preference which is difficult to address. On ranking the Risk criteria as "somewhat risky", one person might give a score of 70, while another might perceive 50 as the appropriate number for such an average risk. This is one of the drawbacks of making relative scorings in a constructed scale instead of direct judgments on an absolute scale. Having had more time, I would have invested more effort into making a commonly agreed scale of measurement such as an objective rating scale for technology maturity level instead of a numerical "proxy" scale ranging from 0–100.

This brings us to the discussion of the value function which was for practical purposes assumed to be linear in the study. However, on some occasions it may be desirable to use a non-linear function. Some may for example state that human reaction to changes in safety or risk levels measured on a direct scale is non-linear.

5.1.2 EVALUATION OF COST-EFFECTIVENESS

As review in section 1.2.3, a Marginal Abatement Cost curve gives us good insight to the cost-effectiveness of each abatement measure. Using input information from DNV on reduction effect, capital cost, operational cost and lifecycle, a MACC for the Grieg case ship has been computed. This MACC chart shows that as much as 44% of one case ship's current emission could be reduced in a cost-effective way, aggregating the 13 measures of negative CATCH values. However this assumes an additive aggregation of the different abatement measures. If we consider a multiplicative aggregation, as proposed in section 3.3.1, the total effect of the cost-effective measures would result in an abatement of about 37% of the ship's current carbon emission level.

However, as computed by the compatibility matrixes in Figure 19, the aggregated effect of implementing "6-propulsion efficiency devices" and "10-contra rotating propeller" would not necessarily be as simple as stated above since these two measures belong to the same abatement measure group of" 113-decrease in propeller loss" from Table 1.

Implementing both "13-hull condition" and "10-air cavity lubrication could also imply some complicated interconnection which could affect the aggregated reduction effects.

This represents 7 % more than the DNV's assessment of the world fleet (Figure 11), (DNV, 2009, #18) which demonstrated that CO_2 emissions by 2030 could be reduced by 30% below baseline in a cost-effective way. Note that the DNV curve may also be assuming additive aggregation.

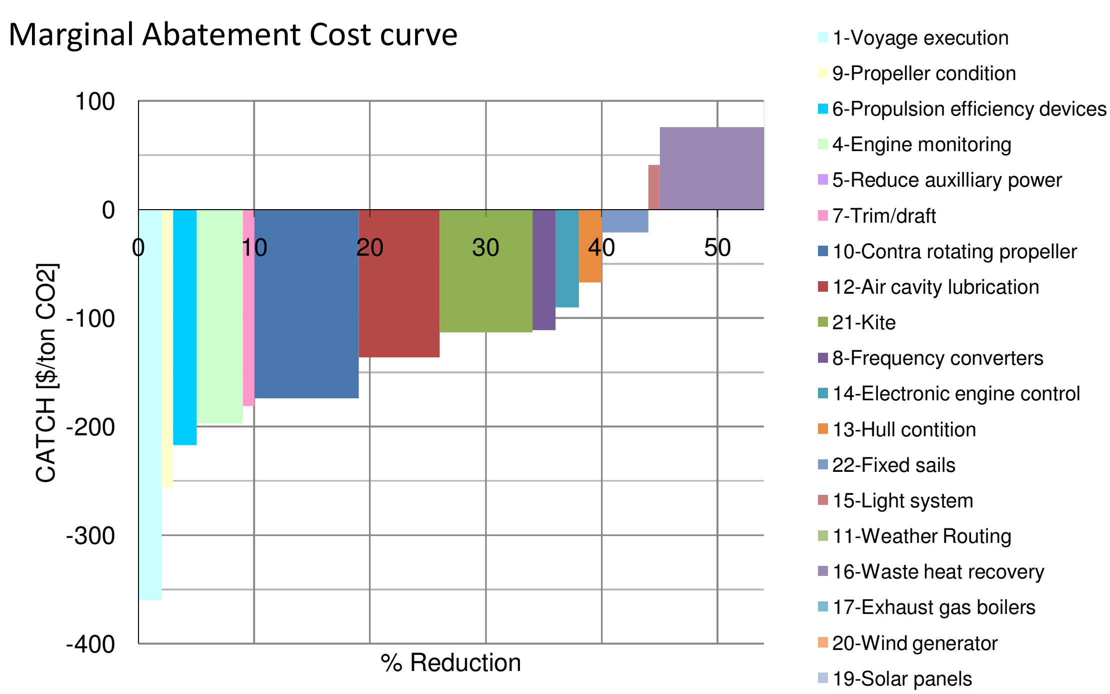


Figure 35: Marginal Abatement Cost curve for the Grieg Ship as result of the cost-effectiveness evaluation

As the ranking in Figure 35 shows," 1 voyage execution" and" 9-propeller condition" which were among the 3 preferred options from the qualitative evaluations, are also in the top 3 most cost effective options in according to the MAC curve. However three of the methods were erased from the former starting set (2, 3 and 18) due to lack of cost data.

The CATCH values, represented on the y-axis in the graph, are calculated using a net present value approach and assumptions from appendix 9.1. The fuel price is estimated to be 475 $/ton, the interest rate is 8% and the remaining lifetime of the ship is 15 years. Input values given from DNV are implementation cost, yearly operating cost, abatement potential and lifecycle of each measure. It is important to note that cost and abatement data given from DNV R&I are only estimations. The uncertainty of these figures is quite high as the data was initially intended for a standard ship in the segment Bulker 35000-59999 DWT-being built within next 4 years with an assumed ship lifetime of 25 years. However regarding the context of my study, these estimations are as good as they get.

Considering only the cost-effective measures with negative CATCH, the average CATCH value is -146 $/ton$CO_2$. Aggregated implementation of the 13 measures would then, in a simplified calculation, result in a yearly saving of about 1 500 000 $ per year for one ship.

$Annual\ savings = C_{av} \cdot E_{CO2} \cdot R$

$Where$:

- $C_{av} = Average\ CATCH\ value\ of\ cost\ effective\ methods\ of - 146\ \frac{\$}{ton\ CO_2}$
- $R = Aggregated\ reduction\ effect\ of\ 37\%$
- $E_{CO2} = Annual\ CO_2\ emissions\ from\ one\ ship\ of\ 27900\ ton\ CO_2$

Considering the sensitivity of fuel cost, illustrated in section 3.8.2, the MACCs show that the rank order is not greatly affected by a change in fuel cost. The only change by fuel price fluctuation is the overall cost-effectiveness of the measures where higher fuel prices increases each measure's cost-effectiveness and lower fuel prices decrease cost-effectiveness.

5.1.3 *Qualitative utility ranking compared to cost-effectiveness ranking*

The figure below shows the qualitative ranking up against the cost-effectiveness-ranking. The differences are apparent - Many of the measures which have been estimated as relatively cost effective have been rated poorly in the qualitative evaluations. These measures include " 6-propulsion efficiency devices" ,"10-contra rotating propeller" and "14-electronic engine control". To a comparable extent, some of the measures with high qualitative ratings are ranked poorly in the cost effectiveness list. Examples are "15-Light system" and "11-Weather routing".

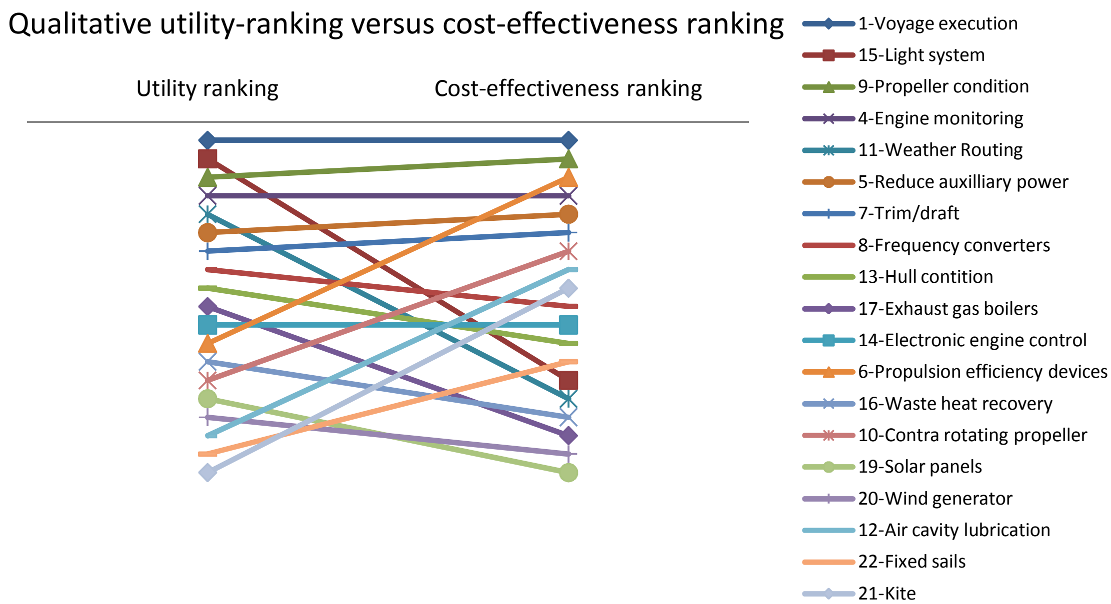


Figure 36: Cost-effectiveness ranking and "utility" ranking

Considering the upper scale however, measures of "1-Voyage execution", "9-Propeller condition", "4-Engine monitoring" , "5-Reduction of aux. power" and "7-Trim/draft optimization" have quite coinciding rankings for both the qualitative and cost-effectiveness evaluations. Considering that the goal is to determine viable measures for the industry, and since both scales are important, these measures could be seen as quite favourable.

5.1.4 AGGREGATED UTILITY AND COST-EFFECTIVENESS EVALUATION

Representing simultaneously the three parameters of utility, cost-effectiveness and reduction effect can give a quite thorough insight to the decision problem. Below is a proposed plot of Marginal Abatement Utility and Cost chart (MAUCC) where the cost-effectiveness is represented by the x-axis and the utility evaluations are represented by the y-axis. The size of each bubble represents the GHG-reduction effect of each measure.

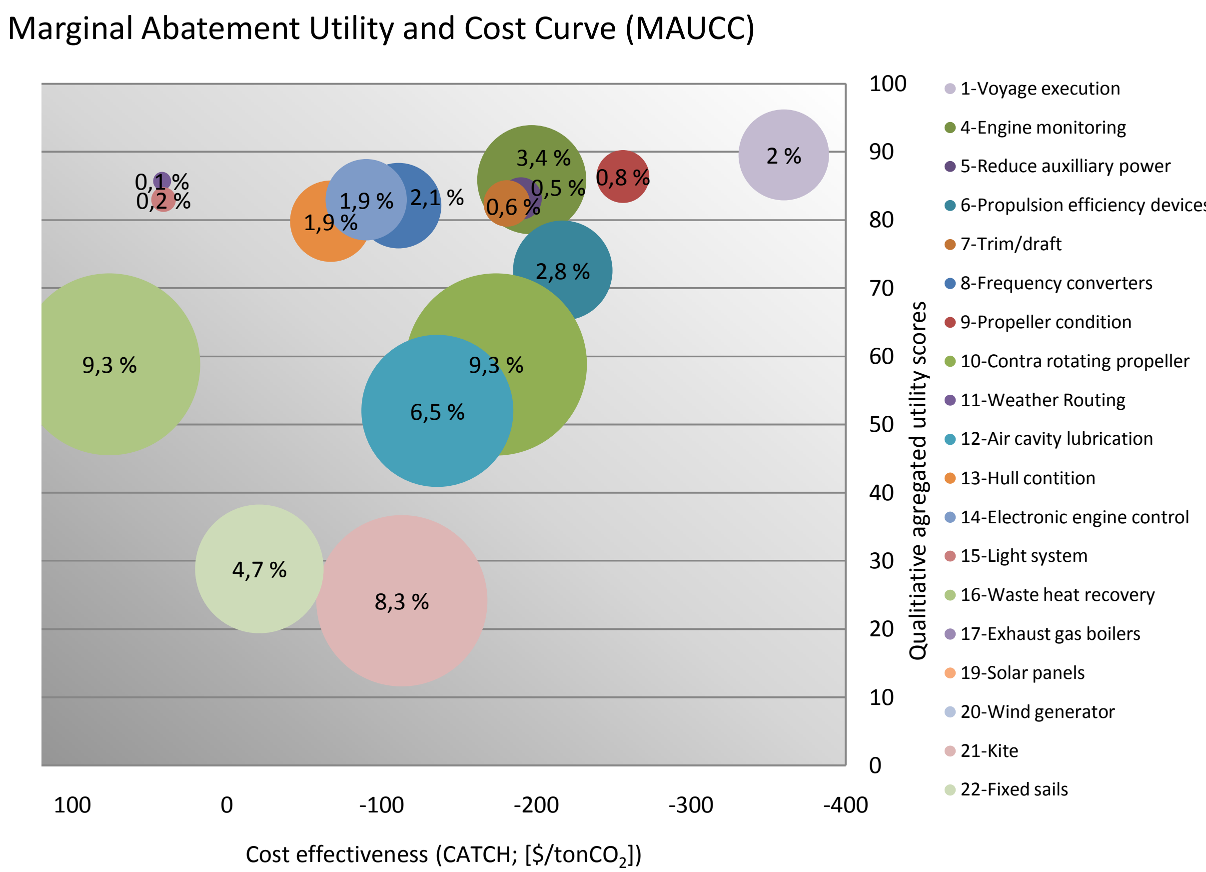


Figure 37: Aggregated Marginal Abatement Utility and Cost chart

Looking at this figure, we see that the preferred measures are situated in the upper right corner while measures in the lower left corner have obtained low score both on cost-effectiveness and utility ratings. As observed, the "1-voyage execution" measure stands out as the best choice for the qualitative evaluation, and especially for the cost effectiveness. This single option stands quite alone, far away from the next best alternatives of "9-propeller condition", "4-engine monitoring" and "6-propulsion efficiency devices".

Rather disappointingly, we can also see that its reduction effect is mediocre (2%). If a ship owner really wanted to focus on reducing emissions, it may be prudent to consider the larger bubbles in the chart, as there most likely will be some hidden costs associated with implementation for each measure. However, with such a high utility score it seems like a safe choice for implementation, and considering its cost effectiveness, improving voyage execution seems like an obvious choice for any ship owner who is looking to reduce emissions. As previously discussed though, this measure is somewhat contingent on route conditions and climate.

The remaining abatement alternatives could be divided into different groups as seen on Figure 38. The first three of these groups have relatively high qualitative scorings, and varying cost effectiveness. Group 4, which consists of the measures air cavity, sails and kite is rated relatively poorly in the qualitative evaluations and has a low cost effectiveness as well.

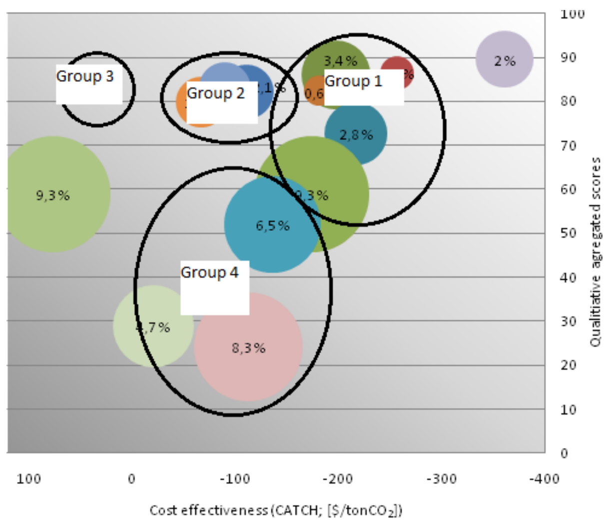


Figure 38: Visualization of different " abatement groups"

- Group 1: High cost-effectiveness, High qualitative ratings, Varying reduction effect
- Group 2: Medium cost-effectiveness, High qualitative ratings, Low abatement effect
- Group 3: Low cost-effectiveness, High qualitative ratings, Low abatement effect
- Group 4: Low/medium cost-effectiveness, Low qualitative ratings, High abatement effect

Observation of the MAUCC could illustrate different strategies to adopt when considering the selection of abatement options. A ship operator which is more determined to maximize cost-effectiveness of the abatement measures, will most likely start with group 1. However if the consideration to utility is more in focus, groups 2 and 3 will be of next interest.

Another strategy to adopt is to consider solely the reduction effects; by implementing first"10-contra rotating propeller" and "16-waste heat recovery" which have reduction effect of 9,3%, closely followed by "21-Kite"as this reduces 8,3% of the carbon emissions.

It is important to note that the y-axis of the MAUCC-curve is based on quite subjective scorings, and with the survey done in a different company in a different country, we should expect to see the bubbles rise and fall. If, for example the"10-Contra rotating propeller" measure was to increase 25 points on the scale, it would seem like a strong candidate with a very high reduction effect. Again I would like to point out that the larger bubbles mainly represent newer emerging abatement measures, and so the knowledge about these is incomplete, causing high levels of uncertainty regarding them. As a result of this, the qualitative scores plunge and the bubble sinks towards the bottom. It is my opinion that research into abatement measures in the maritime sector should focus on getting these bubbles up towards the surface and create new and exciting – as well as viable – options for emissions reduction.

Another interesting observation to the MAUCC chart is that measures with high utility scores does not necessarily imply poor cost effectiveness. As seen in the figure, most of the measures have been attributed a qualitative score over 70 points, and amongst these measures, the cost-effectiveness varies a lot. This observation could somewhat disprove the existence of an evident conflict between cost effectiveness and utility.

I initially planned to include the cost evaluation in the decision model and add the qualitative scores in order to obtain a final aggregated score including all the 5 criteria of cost-effectiveness, risks, complexity and technical maturity. I moved away from this approach because the normalization of the cost into figures between 0 and 100 was difficult since the CATCH range spanned from -360 [$/ton CO_2] to 6556 [$/ton CO_2] with most of the measures lying in the range of 0 to-300 [$/ton CO_2] . The weight of the cost is also quite controversial since this weight will probably vary to a large extent depending on the person who is assigning it. Giving cost its own dimension allows the viewer to decide how much emphasis to put on it, and so I eventually found it most prudent to extrapolate it from the other 4 criteria.

One could say that the role of a ship *owner* is to emphasize the importance of cost effectiveness while a ship *operator* would want to maximize the importance of the utility evaluations since these affect the operation of the measure during its lifecycle. If so, the two roles will find coinciding interests in some measures, and opposing interests in others, as the MAUCC in Figure 37 shows. Nevertheless, they will have much to discuss in evaluating future and present abatement measures, and charts such as the ones I have included in this chapter seem like an important requisite and a good starting point for an enlightened and fruitful debate.

5.1.5 *FACTOR WHICH COULD HAVE AFFECTED THE RESULTS*

Concerns which could have affected the results are:

- The already implemented measures: Grieg Shipping Group have already implemented several abatement measures onboard their ships. Among these are optimization of hull coating intervals, installation of Mewis duct, and installation of energy management software. This could have affected the qualitative rankings where the measures which are known could have obtained higher overall qualitative scores.

- The few number of participants: The MCDA survey included only 8 participants and to conclude on a specific trend, it should have included more people.

- Not all abatement measures were commonly known by all participants in the study. This was unveiled by question 2 in the survey (ref. appendix 9.2). This lack of knowledge regarding some of the more rare abatement measures could have affected the qualitative evaluations and adds higher uncertainty to the results. This was to be expected, however, and could be representative for other companies as well.

- Participants were asked to rate scores based on "gut feeling", Giving that The MCDA is not an exact study and the result are affected by subjective preferences.

- Even though the results of the MCDA have shown a clear priority ranking of abatement options both "cost wise" and "utility wise", the results should be handled with care and determining an overall value-ranking should by no means be viewed as the end of the analysis. The output result of the model should rather be seen as another step in furthering understanding and promoting discussion about the evaluation and selection problem .

  (Belton and Stewart, 2003, #23).

5.2 USE OF A FORMAL DECISION FRAMEWORK IN SELECTING ABATEMENT MEASURES

One of the main objectives of this study was to investigate if multicriteria decision analysis could be a helpful tool in the process of evaluating and selecting abatement measures in shipping. In relation to this, a range of benefits and challenges is presented herein, all related to the MCDA case study which was carried out at Grieg Shipping Group.

5.2.1 KEY CHALLENGES TO USING A DECISION FRAMEWORK FOR THE STUDY.

- Identification of abatement measures: Since the definition of a GHG abatement measure is still somewhat unclear, identifying all existing abatement measures is not an easy task. Literature regarding GHG abatement measures is primarily found in articles, reports and from the internet. The literature is considered more as best practice descriptions, rather than scientific theory.

- Choosing which measures to include in the starting set: As mentioned, proper scientific literature on abatement options is rare and the task of finding information regarding requirements and constraints for different abatement measures is not an easy one. This was especially difficult since the properties of abatement options differ so much with ship type and ship size. The configuration of the starting set was done by me as a facilitator and with my limited technical knowledge I would have preferred to include the participants of the survey earlier and included them in the screening process.

- Finding accurate data on cost and reduction effect of the different measures: Since information on abatement measures is quite rare, data about abatement reduction effect and cost was difficult to find. This also led me to the choice of only including abatement options where cost and reduction effect data from DNV was available in the evaluation.

- The time and effort required may scare companies from considering a structured decision making process. However a very simple MCDA approach is likely to be as effective in achieving many of the benefits of a formal decision analysis. The actual case study was achieved within a couple of days at the shipowner office. However after completing the study, I realized that the study would have benefited from including participants earlier in the process to help in identifying the alternatives with necessary requirements and constraints.

In general, other challenges in a MCDA process could be related to the ownership of knowledge, the understanding of problem context and the time required for planning during a MCDA process. However in general, these kinds of problems are as likely to occur with any other formal group decision processes.

5.2.2 *KEY BENEFIT OF USING A DECISION FRAMEWORK IN THE STUDY*

- Structuring the decision making: Using a formal decision framework contributes to structure in the decision process. The important milestones in the decision timeline are organized and makes it easier to get an overview of the many characteristics related to each abatement option

- Learning: One of the principal benefits from conducting a MCDA is helping decision makers learn and understand the context of the decision problem. Having a structured approach and including several stakeholders forces hard thinking and communication from each contributor. Decision makers have to organize the different judgments and viewpoints in a way which guides them in identifying the preferred abatement alternatives.

- Transparency in the decision process: An MCDA makes decisions traceable, and enables decision makers to justify and explain their decision to external parties. The weighting of criteria and the scores are explicit information which could serve as an audit trail.

- Inspire, motivate, commit: Even if the decision makers are the ones with the deepest insight to the decision problem, the MCDA process could include other participants to commit to the decision as well, and learn in the process.

After reviewing the different problems and benefits encountered during the case study I consider the use of an MCDA process as a helpful tool in assisting evaluation and selection of abatement measures. Most of the challenges are related to the identification and configuration of abatement alternatives in the first steps of the analysis. I see this stage as the main obstacle in proceeding with the case study.

Furthermore, I wouldn't view the resulting ranking as the main benefit, at least not in this study. This is due to the fact that the output results are uncertain and may not be as valuable as initially thought. I would rather say that the main benefit from the actual case lies in the insight and understanding of the nature and process of the decision problem. General trends are observed and conflicting goals are brought to attention. The decision model offers also a general insight to the process of the analysis as it is a valuable tool for making information and viewpoints explicit and open to different stakeholders. The process in itself provides an important platform for discussion and communication between the stakeholders in addition to sharing knowledge and committing participants to involvement in the decision making.

Of course planning and implementation of the model could have been improved, and my lack of experience and knowledge about how to carry out an MCDA made the nature of the analysis somewhat experimental.

The process of selecting and implementing abatement measures is difficult to address generally as the decision problem can be very different from case to case. The ship type, the ship size, the fleet, the routes and the cargo are only some of the many variables which will affect both the relevant alternatives to evaluate and the scores which are attributed to each abatement alternative. Also, each case should preferably be evaluated individually, and by stakeholders in close contact to the ship and the operational procedures.

Although I would say that the process of learning and understanding the decision context during the analysis is the main benefit of this study, the feedback given after the analysis also plays an important role. Decision makers reflect and review the information they have provided, the judgments they have made , and try synthesize them into valuable information. The question of whether or not the model will be a successful catalyst for discussion about the problem could also depend al lot on the how the feedback is provided. Simple representations with figures and visual displays are effective tools to reflect back information and provide the basis for further investigations on uncertainty and sensitivity.(Belton and Stewart, 2003, #23)

As for the choice on MCDA method, it needs to be mentioned that I did not have the time to gain the required knowledge to be able to choose the best method suited for this kind of decision problem. The case study should be seen as a test of using MCDA as a general process (rather than a specific existing MCDA-methodology). There is a wide range of different MCDA-methodologies to implement, especially regarding the different methods to assess scores and quantify weights. Even though I evaluated the use of some outranking methods, the AHP method and others, I finally chose to use MCDA on a relatively basic level in order to simplify the process.

6 CONCLUSION

This study can be regarded as a trial of possible methodologies to evaluate GHG abatement measures in shipping. The main idea was to develop a multicriteria decision framework including factors other than cost-efficiency which are important to a selection of most fitted abatement measures. The open hatch bulk vessels of the Grieg fleet served as a case.

MACC methodology for assessing cost-effectiveness was integrated into a 7-step decision framework to holistically evaluate 25 potential abatement measures to a case fleet of open hatch bulk carriers. In this way, the combined decision framework assesses several factors such as risk, technical maturity and complexity in combination with cost effectiveness. The results of the analysis yielded a cost-effectiveness ranking and a utility ranking. These two evaluations were then aggregated into a Marginal Abatement Utility and Cost chart (MAUCC) where all three parameters; cost-effectiveness, utility score and reduction effect were presented at once(Figure 37).

A MAUCC chart can provide a solid foundation for discourse regarding abatement measures because it summarizes a lot of important information in an easily visible manner without overly simplifying. It also acts as a common platform which participants can use for reference in evaluating different strategies to adopt in selecting abatement measures.

In the case study, the measures of “1-Voyage execution”, “9-Propeller condition”, “4-Engine monitoring”, “5-Reduction of aux. power” and “7-Trim/draft optimization” received relatively high rankings for both utility and cost-effectiveness. The more emerging measures “21-Kite” “22-Fixed sails” and ”12-Air cavity lubrication” had a high reduction effect and were quite acceptable in relation to the cost effectiveness. However these measures were attributed relatively low utility scores which is a pity since they represent a potentially high reduction effect.

During the case study, it seemed clear to me that the process of implementing a formal decision framework with qualitative elements had an indirect educational effect. In rating the qualitative attributes for each measure, participants give a personal opinion both on measures and on their corresponding attributes. Some measures are bound to be less known than others, or even previously unknown. And even though a measure is well known, there might still be criteria that have not previously been considered to a sufficient extent. Thus the process of evaluating qualitative criteria is an educational one, forcing participants and decision makers into hard thinking. With that, knowledge of abatement measures and their corresponding criteria increase. More importantly however, is that it raises awareness of the current level of knowledge of abatement measures for each participant. In determining which criteria are the most important, the process also raises awareness of company priorities. In carrying out my case study, it was surprising to find that no participants chose the criteria of cost-effectiveness as first priority. Criteria of risk considerations and technical maturity was overall preferred and perceived as more important to a choice of abatement measures. Further research into the educational effects of such a process is suggested to obtain deeper insights, however it seems clear to me, that the effects are positive – both for the company and inevitably for the environment.

Upon analyzing the MAUCC chart, two interesting findings were observed. Firstly the results suggested that there was no evident conflict between the qualitative utility scores and cost-effectiveness. Abatement measures with a high utility score were not necessarily less cost-efficient than the measures with lower utility scores. This could support a theory that the cost-effectiveness and utility are not conflicting properties. The result of this is that some choices come off as no-brainers; they seem like obvious choices regardless of situation. In my case study, an example of this was optimizing voyage execution, which seemed to be in a league of its own both in utility and cost-effectiveness. Since the qualitative assessments are bound to vary from company to company, we cannot conclude that this measure will be as obvious elsewhere, but the observed tendency that cost-effectiveness and utility are not conflicting properties would suggest that other measures might present themselves as obvious choices for other companies. Of course, this also works the other way around – some measures are deemed cost-inefficient as well as having poor utility scores. This has a value in its own in that a company can exclude it from the discussion until the situation changes. To summarize, it would seem like in the world of abatement reduction investments – there is not necessarily a standard cost/utility relationship. In other words, you don't always get what you pay for, and in some cases you can find a real bargain! A closer investigation regarding the relationship between cost-effectiveness and qualitative attributes is suggested for further study. If this tendency is supported, it would make knowledge about abatement measures and their qualitative attributes even more important, and thus give methodologies with qualitative elements such as the one I have explored in this thesis increased value because of their indirect educational effect.

The other interesting observation that becomes apparent when analyzing the MAUCC chart is the tendency that the more emerging and innovative solutions like "12-air cavity", "22-Fixedsails" and "21-Kite" were attributed relatively low utility scores. Disappointingly, these are also amongst the measures with the highest reduction effects. Consequently, it is advised to increase research and documentation on these emerging abatement measures in order to increase how they are perceived qualitatively. Even though these new and exciting technologies are still somewhat experimental, they have the potential to become viable options for emissions reduction with high reduction effects.

Although it is difficult for me to accurately determine how the decision process at Grieg took place before I started my case study, it seems prudent to assume that cost-effectiveness was the main guiding factor. In my case study it seems evident that emerging "unknown" measures are rated qualitatively low, while more well-known measures score highly – especially if they have already been implemented or the employees have had some experience with them. Even though Grieg has not systematically evaluated these measures qualitatively previously, it seems likely that qualitative evaluations have affected decisions. A formal decision aid including qualitative elements can enrich this process and increase transparency, as well as increasing knowledge and awareness in the organization. This might in itself have a positive environmental impact, as increased knowledge of measures and their attributes will reduce the "fear of the unknown" and inevitably help the emerging abatement measures with the higher reduction potentials bubble up towards the surface and become viable alternatives. It seems likely that companies who succeed in successfully implementing emerging abatement measures ahead of the crowd will gain a competitive advantage, as well as good Public Relations for positioning themselves as an environmentally friendly company. A further investigation of these benefits is suggested as further study.

To conclude, I would say that the usage of a decision framework in answering the problem of selecting abatement measures in shipping has been quite helpful. The model contributed a lot to structuring both the process of the decision and the many factors included in it. Using a formal decision framework with qualitative criteria does not only aid in identifying the preferred abatement measures, but the process will also increase knowledge and awareness among the participants, something which might ultimately lead to a competitive advantage for the company. Nothing good is ever easy however, and I have pointed to several barriers to implementation. Nonetheless I would recommend the use of such a decision framework to any decision maker considering emission reduction in shipping.

7 FURTHER WORK

As mentioned before, the uncertainty regarding cost-effectiveness and reduction effect is one of the main barriers to implementation of cost effective abatement measures.

In this study, rough estimations on cost from DNV R&I have been used. If one were to increase the certainty of each reduction effect and obtain more accurate cost data, I would recommend contacting suppliers, manufacturers, shipyards or ship owners and ask for more precise data regarding the abatement measures to implement on the Grieg Ships.

The aggregated abatement effect of implementing multiple measures is also a topic of discussion. The multiplicative aggregation calculation used in this study may not be accurate and the effect of implementing two methods which are not compatible (coloured red in the compatibility matrix in Figure 19) would probably have an even more complicated aggregated reduction effect. Full scale sea trials and experiments regarding this matter would have been an interesting continuation of the compatibility issues.

As for the utility evaluations, these include many subjective scorings which are inevitably affected by many influences and inherently uncertain. One improvement to mitigate this effect could have been to make the questions more robust, precise and less open to subjective interpretation. The computation of absolute qualitative scales instead of a constructed proxy scales is another possible improvement.

Overall the decision framework applied in this study should be regarded as an experiment in using formal decision analysis. The model maintains an open structure which may be adapted further by changing the choice of criteria and measures as well as weighting and scoring techniques. There are a wide range of different multi criteria decision methods and framework choices, and further investigation into decision theory would hopefully reveal more appropriate methodologies for the diverse settings in which emission reduction decisions are made.

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9 APPENDIX

9.1 APPENDIX 1: ASSUMPTION USED FOR COST-EFFECTIVENESS CALCULATIONS

Assumptions used for calculations of cost and emissions		
Remaining life time of ship	15	year
Price of ship	55	mill$
Fuel price	475	$/tonn
SPC IFO	180	g/kWh
Fuel type (both main and aux. engines)	IFO 380	
Speed	16	knots
Main engine MCR	10500	kW
Main engine NCR	9450	kW
Auxilliary MCR	760	kW
Auxilliary NCR	684	kW
Power = $314{,}08 \cdot v^2 - 7845{,}9 \cdot v + 54338$		
Operating days (at sea) pr year	220	days
Fuel consumption pr day MAIN	41	tonn
Fuel consumption pr day AUX	3	tonn
Interest rate	8,0 %	
C_f CO_2 content in IFO 380	3,11	tonCO2/ton fuel
Annual fuel consumption	8980	ton
Annual CO2 emissions pr year IFO	27900	ton CO2
Annual fuel cost	4265500	$

9.2 APPENDIX 2: SURVEY CARRIED OUT AT GRIEG SHIPPING GROUP

Question 1 and 2:

Hvor mye av dagens CO2-utslipp fra skip (GSG-skip) tror du vil kunne bli redusert fram mot 2020?

- 5 %
- 10 %
- 20 %
- 30 %
- 40 %
- annet

Nedenfor er det presentert et sett med 22 mulige tiltak som kan implementeres for å redusere CO2 utslipp fra skip. Noen er tekniske, andre operasjonelle. De fleste tiltakene går ut på å øke energieffektiviteten mens andre er rettet mot bruken av fornybar energi ombord på skipene.

Kryss av for hvorvidt du er godt kjent med tiltakenes eksistens.

	Ja, dette tiltaket kjenner jeg til, og jeg vet at det er blitt prøvd ut	Ja, dette tiltaket høres kjent ut	Nei, dette tiltaket kjenner jeg ikke til
1 Voyage execution: Refers to the potential improvement of the voyage execution in means of speed and fuel consumption of main engine			
2 Speed reduction(fleet increase): Reduce speed of voyage by increasing the total cargo capacity in nr of vessels			
3 Speed reduction: Increase the loading and offloading efficiency in port (shorter time in port means slower speed in voyage)			
4 Engine monitoring: Closer monitoring of the engines condition, maintain optimal engine load			
5 Reduce auxiliary power by ensuring optimal load on auxiliary engines.			
6 Propulsion efficiency devices: Propeller boss cap fins, ducts, vans etc.			
7 Trim/draft: Trim optimization of the ship during voyage.			
8 Frequency converters			
9 Propeller condition: Increase propeller polishing to optimal			
10 Contra rotating propeller: installation of new propeller of type contra rotating			
11 Weather Routing: Better decision support to the crew with recommendation of the most optimal route based on forecasted weather and currents			
12 Air cavity lubrication: Decrease the hulls frictional resistance trough lubricating the hull with air			
13 Hull condition: Maintain optimal hull friction by using anti fouling paint and optimum hull cleanings			
14 Electronic engine control: is a type of electronic control unit that determines the amount of fuel, ignition timing and other parameters an internal combustion engine needs to keep running			
15 Light system: Reduce lighting and energy consumers onboard ship.			
16 Waste heat recovery: Adding turbosystem to recover the exhaust gas energy			
17 Exhaust gas boilers: use engine waste exhaust heat to get warm water			
18 Cold ironing: Reducing aux power need in port by receiving electricity input from shore			
19 Solar panels: Reducing aux power need by procuring solar energy			
20 Wind generator: Decrease the main engine load by using wind generators as bi-propulsion power			
21 Kite: Decrease the engine load by using kite as bi-propulsion power			
22 Fixed sails: Decrease the main engine load by using fixed sails as bi-propulsion power			

Question 3:

Har du noen kommentarer til de hvorvidt de forskjellige tiltakenes er egnet og gjennomførbare i praksis ombord på Grieg sine skip. Kommenter.

1 Voyage execution: Refers to the potential improvement of the voyage execution in means of speed and fuel consumption of main engine	
2 Speed reduction(fleet increase): Reduce speed of voyage by increasing the total cargo capacity in nr of vessels	
3 Speed reduction: Increase the loading and offloading efficiency in port (shorter time in port means slower speed in voyage)	
4 Engine monitoring: Closer monitoring of the engines condition, maintain optimal engine load	
5 Reduce auxiliary power by ensuring optimal load on auxiliary engines.	
6 Propulsion efficiency devices: Propeller boss cap fins, ducts, vans etc.	
7 Trim/draft: Trim optimization of the ship during voyage.	
8 Frequency converters	
9 Propeller condition: Increase propeller polishing to optimal	

Remaining options are not shown here.

Question 4,5 and 6:

Sett at ethvert tiltak har disse fem egenskapene/kriteriene knyttet til seg:
- Kostnader: Tiltakets kostnad med hensyn til investering, drift, vedlikehold osv. i en livssyklussammenheng.

- Teknisk modenhet: Hvorvidt tiltaket er modent til implementering. Er teknologien fortsatt under utvikling, er den testet ombord på skip eller har den allerede vært operasjonell i mange år.

- Sikkerhet: Hensyn til hvilke risikomomenter som er involvert i implementering og drift av et tiltak. F.eks. endringer i manøvrering, stabilitet, framdrifts pålitelighet osv.

- Implementeringskompleksitet: Mål på kompleksiteten av å implementere et tiltak med hensyn til antall personer involvert i implementeringsprosessen, forberedelser, installasjoner, docking osv.

- Operasjonskompleksitet:Mål på kompleksiteten av å drive et tiltak med hensyn til personer involvert i driftsfasen, mengde vedlikehold, tillegg på arbeidsbelastning.

Hvilke av disse kriteriene føler du burde vært høyest prioritert i forbindelse med valg av tiltak?

Kostnader	Teknisk modenhet	Sikkerhet	Implementingskompleksitet	Operasjonskompleksitet
○	○	○	○	○

Gitt at du gir kriteriet med høyest prioritet fra forrige spørsmål 100 poeng hvor mange poeng fordeler du på de andre kriteriene med en score mellom 0 og 100

- Kostnader	- Teknisk modenhet	- Sikkerhet	- Implementingskompleksitet	- Operasjonskompleksitet

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Ranger disse tiltakene med utgangspunkt i kriteret TEKNISK MODENHET. (Sett 100 poeng på det tiltaket du mener er mest teknisk utviklet og gå videre nedover til det tiltaket som du mener er minst utviklet. Sett gjerne samme nr. for tiltak du mener har lik rangering)

1 Voyage execution: Refers to the potential improvement of the voyage execution in means of speed and fuel consumption of main engine	
2 Speed reduction(fleet increase): Reduce speed of voyage by increasing the total cargo capacity in nr of vessels	
3 Speed reduction: Increase the loading and offloading efficiency in port (shorter time in port means slower speed in voyage)	
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6 Propulsion efficiency devices: Propeller boss cap fins, ducts, vans etc.	
7 Trim/draft: Trim optimization of the ship during voyage.	
8 Frequency converters	
9 Propeller condition: Increase propeller polishing to optimal	
10 Contra rotating propeller: installation of new propeller of type contra rotating	
11 Weather Routing: Better decision support to the crew with recommendation of the most optimal route based on forecasted weather and currents	
12 Air cavity lubrication: Decrease the hulls frictional resistance trough lubricating the hull with air	
13 Hull condition: Maintain optimal hull friction by using anti fouling paint and optimum hull cleanings	
14 Electronic engine control: is a type of electronic control unit that determines the amount of fuel, ignition timing and other parameters an internal combustion engine needs to keep running	
15 Light system: Reduce lighting and energy consumers onboard ship.	
16 Waste heat recovery: Adding turbosystem to recover the exhaust gas energy	
17 Exhaust gas boilers: use engine waste exhaust heat to get warm water	
18 Cold ironing: Reducing aux power need in port by receiving electricity input from shore	
19 Solar panels: Reducing aux power need by procuring solar energy	
20 Wind generator: Decrease the main engine load by using wind generators as bi-propulsion power	
21 Kite: Decrease the engine load by using kite as bi-propulsion power	
22 Fixed sails: Decrease the main engine load by using fixed sails as bi-propulsion power	

There were three more questions similar to question 6 in the survey to score options accordingly to the3 remaining criteria. However these are very similar to Q6 and are not shown here

Question 11, 12 and 13 related to barriers:

Gitt at flere av de overnevnte tiltakene er kostnadseffektive,(Rederiene kan tjene penger på å implementere tiltakene i et livssyklusperspektiv pga. redusert fuelforbruk) Hvilke faktorer/barrierer tror du da kan hindre innføringen av disse tiltakene?

Hvilken del av rederiorganisasjonen tilhører du?

- ○ Mannskap
- ○ Prosjektavdeling
- ○ Superintendent
- ○ Høyere ledelse
- ○ Markedsavdeling
- ○ Innkjøpsavdeling
- ○ HR/CSR avdeling
- ○ Regnskapsavdeling
- ○ QA avdeling

Med utgangspunkt i den delen av organisasjonen du tilhører, hva ser du på som den største utfordringene i forbindelse med implementering av utslippsreduserende tiltak. (kan krysse fler alternativer)

- ☐ Forhold knyttet til kontrakt med kunde
- ☐ Forhold knyttet til markedet-sykluser, drivstoffpriser osv.
- ☐ Tekniske faktorer som gjennomførbarhet, vedlikehold, implementering av ny teknologi.
- ☐ Usikkerhet knyttet til nytteverdi og pris.
- ☐ Forhold knyttet til organisasjonen, opplæring av mannskap, rapportering av resultater, økt arbeidsbelastning.
- ☐ Andre forhold