NTNU – Trondheim
Norwegian University of
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Multi Criteria Decision Analysis (MCDA) in the Norwegian Maritime Sector

Adding Environmental Criteria in Maritime Decision Support Systems

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Oppgavetekst/Problembeskrivelse This thesis aims to develop a MCDA model for Norwegian maritime transportation covering cost and environmental aspects. The objective is to facilitate the selection of the most preferable option for cargo transportation for Norwegian ship owners. This objective is met by performing a MCDA using the analytic hierarchy process (AHP), enabling pairwise comparison of cost and environmental aspects against alternative performance criteria. Through interviews and questionnaires, weighting of the criteria is elicited from the main decision makers. This approach is applied to analyses carried out in three case studies for Egil Ulvan Rederi AS, Aasen Shipping and Seaworks, where different cargo transportation modes are compared over the operational phase for a specific route along the Norwegian coast.	
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Preface

This thesis has been conducted at the Norwegian University of Science and Technology (NTNU), spring semester 2014, at the Department of Industrial Economy and Technology Management. The thesis is a part of the specialization in Environmental Management and Politics at the Industrial Ecology graduate programme.

The study undertaken will contribute to an overarching project, SUSPRO – Sustainable Ship Production in Global Fluctuating Markets. The primary goal of this study has been to contribute to the development of decision support tools for the Norwegian maritime sector, and test one such approach on a case study for the ship owning company Ulvan Rederi AS.

We would like to express our gratitude to our supervisor Annik Magerholm Fet for all the direction and comments during the study, and the opportunity to apply this research to the maritime industry. We are also grateful to our co-supervisor Dina Margrethe Aspen for the invaluable guidance, support and inspiration during the research process. We would also like to thank Ivar Ulvan at Egil Ulvan Rederi AS, for the cooperation in the case study. On that note, we would like to give additional thanks to Aasen Shipping and Seaworks for providing important data used in this thesis.

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Abstract

There are several current challenges to the competitiveness of the Norwegian maritime sector. The short sea shipping industry is facing tougher requirements on the environmental performance of vessel technologies, mainly from the quality and type of fuels utilized. Other challenges are high production costs and increasing global competition. For Norwegian ship owners, an additional challenge is the increase in road cargo transportation. A technology shift in the maritime sector may be necessary to meet these challenges. In this thesis, we argue that in order to make this shift happen, better decision support tools (DST) must be implemented.

In this thesis, a Multi-criteria Decision Analysis (MCDA) model has been made for the Norwegian maritime sector. The Analytic Hierarchy Process (AHP) has been applied to a case study at a Norwegian ship owner, based on a vessel investment at Egil Ulvan Rederi AS. In this study, marine diesel oil (MDO) and liquefied natural gas (LNG) have been identified as alternatives. To obtain the most preferred alternative, the ship owner’s preferences for the following criteria were identified; air emissions, cost, technical performance and risk. The results shows that LNG was the most preferred alternative. This thesis proposes a systematic approach combining MCDA and Systems Engineering (SE).

The results indicate the importance of including environment as a parameter in maritime decision-making, and may be especially important in areas subject to strict regulations on ship exhausts. It also indicates that MCDA, and AHP, can be used to aid decision makers in structuring their priorities in a decision-making context.

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Abbreviations

AHP	Analytic Hierarchy Process
Alternatives	All options or choices from which the decision maker can make a selection
CO_2	Carbon dioxide
Criteria	Values, objectives, attributes, key factors or characteristics inherent and relevant to the alternatives
DST	Decision Support Tool
ECA	Emission Control Area
GHG	Greenhouse Gases
IMO	International Maritime Organization
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LNG	Liquefied Natural Gas
MAVF	Multi-attribute Value Function
MCDA	Multi-criteria Decision Analysis
MDO	Marine Diesel Oil
NO_x	Nitrogen oxides (includes nitric oxide, NO, and nitrogen dioxide, NO_2)
SE	Systems Engineering
SFOC	Specific Fuel Oil Consumption/Specific Fuel Consumption
SECA	Sulphur Emission Control Area
SO_x	Sulphur oxides
System	Set of elements or components that have a purpose or function in common and interact with each other

1 Introduction

In Norway today, as much cargo is transported on land as on sea. This despite that short sea shipping is generally more energy efficient and less polluting than its land based counterpart, and frees up road traffic (Bengtsson et al., 2014; Monsrud, 2009). The short sea shipping industry in Norway is working for a shift in this distribution, with the aim that a bigger share of the cargo freighting in Norway falls to maritime transport. The short sea shipping sector must however prove economical, as well as environmental feasibility for this to shift to be viable. The industry is facing tougher requirements on the environmental performance of the current technologies, mainly from the quality and type of fuels utilized in the sector. Consequently, in the coming years, increasing pressure on greenhouse gas reduction will enforce stricter regulations on air emissions from the industry (Bengtsson et al., 2014).

The main challenges to competitiveness in the Norwegian maritime sector are understood as high production costs, increasing competition at the global level, and increased environmental regulations. The competitiveness of the Norwegian maritime sector is dependent on meeting these challenges. As a result, a technology shift in the maritime sector may be necessary to make short sea shipping of cargo a more attractive alternative. That means cleaner technology, leaner production and overall higher material, cost and energy efficiency. There is thus an explicit demand for better technology alternatives. In this thesis, we will argue that in order to make this shift happen, better decision support tools must be implemented.

The thesis will contribute to an overarching project, SUSPRO – Sustainable Ship Production in Global Fluctuating Markets. The project is a collaboration between academia and industry stakeholders, and aims to meet these challenges by increasing sustainability while ensuring high environmental and economic performance. This requires innovations in production management beyond pollution control and compliance to regulations. Applying these will, according to Rao and Holt, contribute to better material efficiency, lower costs, emissions and energy efficiency (2005).

A challenge however is to be able to implement these measures. An important aspect of the SUSPRO project is the development of decision support tools for the industry. In this thesis, a decision support tool will be selected, adjusted and implemented to a case study representing a vessel investment at a Norwegian ship owning company. The aim of this study is to apply this method to see how this can be utilized in the Norwegian maritime sector, and to assess the viability of liquefied natural gas (LNG) as a technology alternative in meeting the challenges faced by the maritime sector.

1.1 Purpose and scope of the study

The primary goal of this study is to contribute to the development of decision supporting tools (DSTs) for application in the Norwegian maritime sector, with the intention to strengthen competitiveness in the sector.

A secondary goal is to test one model of such tools in a case study for Ulvan Rederi AS.

The principal focus of the study is on the selection process of vessels in the Norwegian maritime sector, specifically in meeting present and future exhaust emission regulations. A natural emphasis is thus placed on technologies that can meet such policies and regulations. Liquefied natural gas (LNG) is highlighted as one such alternative.

Efforts in promoting short sea shipping of cargo will be discussed as another challenge to the Norwegian maritime sector.

1.2 Research questions

The goals will be reached by answering the following questions:

Can MCDA models, specifically the Analytic Hierarchy Process (AHP), be used to facilitate the selection process for the best technical solution in ship selection problems?

Which criteria should be considered in ship investment from the ship owner's perspective?

Is AHP applicable for the case company when it comes to selections between LNG vessels and marine diesel fueled vessels?

1.3 Description of the chapters

In this thesis, Multi-criteria Decision Analysis (MCDA) methods are generally described. One of the MCDA methods, the Analytic Hierarchy Process (AHP) is further applied to a case study from the ship owner's perspective.

In chapter 2, the background information required to develop the case study is described. Challenges to competitiveness in the Norwegian maritime sector is also explored. This chapter describes road and sea transportation in Norway, environmental impacts of marine exhaust, technologies used for maritime cargo transportation, and the importance of decision-making in ship investment. Chapter 3 covers a review of systems thinking theory and describes the MCDA methodology. Additionally, this chapter illustrates some of the applications of MCDA models in the transport sector and an overview of the most common models employed in decision-making problems. AHP has been applied to the case study; therefore, this chapter also contains a thorough description of this method. At the end of chapter 3, a stepwise approach is proposed in order to apply Systems Engineering (SE) to MCDA problems. Chapter 4 defines the case study, which through the application of AHP and the proposed stepwise approach, models the decision process for ship selection between two alternatives: (1) a MDO fueled cargo vessel and (2) a LNG fueled cargo vessel. In chapter 5 and 6, a brief discussion and conclusion are presented respectively.

2 Background

In this chapter a framework for ship investment, the Norwegian transport sector, environmental regulations and propulsion technologies is presented. Additionally, an overview of LNG is provided.

2.1 Ship investment

The regulations and the market in the maritime sector are changing rapidly and it is necessary to find alternatives that can provide solutions, allowing the adaptation of the sector in a sustainable manner. It is important for instance, to meet environmental regulations; however, solutions have to be technically possible and economically feasible. Therefore the maritime sector requires tools or methods to make easier and more reliable the decision-making process. As a result of applying these tools, the best solution for investment problems is obtained.

Ship investment is an extremely complex decision. Ship orders for new buildings are dependent on the demand for carrying capacity. Thus, essentially the main reason that a ship owner has to build a new vessel is to meet the demand. Additional to high capital costs, the uncertainty of the market and the competition, imply a complicated decision problem for ship owners. In the first place, the ship owner has to determine whether to invest on a ship. The next step is to identify what type of vessel the ship owner is willing to invest on (Luo and Fan, 2011). Investing on ship building might require an open view and consideration of many criteria such as technological costs, learning effects, fuel price volatility (DNV, n.d.), technological characteristics in design and shipbuilding innovation, as it has been done in different studies (Xu and Yip, 2012). In addition, psychological factors can influence the investment decision (Rousos and Lee, 2012) and should be included in any decision process.

The decision procedure for ship investment considers not only the possibility of building new vessels but also the possibility of acquiring second handed ship (Luo and Fan, 2011). In any case, if there is enough demand for a new vessel, a decision has to be made. Luo and Fan (2011) illustrate the investment decision procedure for ship owners as presented in Figure 2.1.

In spite of the different possible designs, economical studies have to come along in order to make a decision whether or not to build a vessel and to select the type of ship to be manufactured. The success of shipping companies is determined by the correctness of the decisions during the investment process. Commonly, ship investment evaluation is based on techniques such as NPV and IRR (Diakomihalis, 2003). This limits and interferes the objective evaluation for ship investment, disregarding for instance, physical information and uncertainties (Xiao et al., 2010).

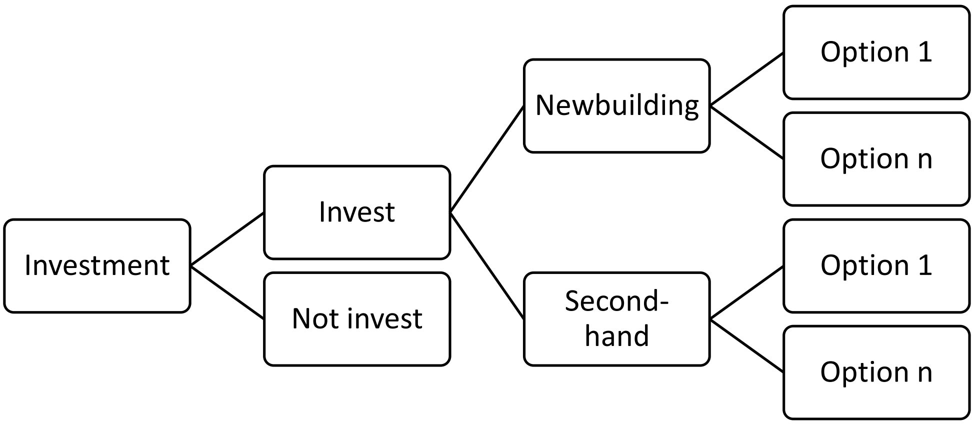

Figure 2.1: Investment decision procedure for ship owners. From Luo and Fan (2011).

The biggest shipbuilding clusters in the maritime industry are Japan, South Korea and China as shown in Figure 2.2, illustrating the distribution of contracts for shipbuilding. From this, Norway participates only with the 0,03% of the contracts (Xu and Yip, 2012).

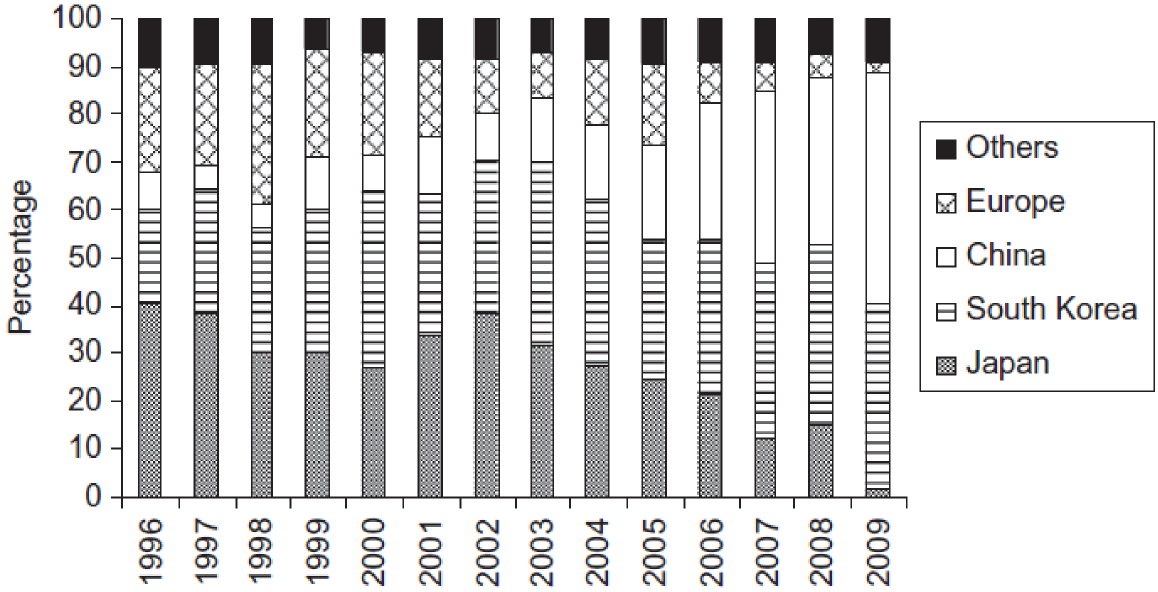

Figure 2.2: Shipbuilding contracts distribution. From Xu and Yip (2012)

Xu and Yip (2011) incorporate in their study the economic analysis of the shipbuilding market and summarize the most relevant economic factors that determine ship investment. In addition, it is stated that the most common variables are the profits, capital stock, interest rate and governmental incentives and expectation. Therefore, the level of confidence that a ship owner perceives from the freight market is determinant at the moment of investing in building new vessels.

Ship owners usually have to face several issues and concerns before making the decision to invest in newbuildings. It is a long process of planning, designing and negotiations until the production phase starts (Maroulis, 2004). Consequently, a good planning activity inside the life cycle of the project is essential in order to achieve a good investment. This means that the ship owner has to look into different conditions that can influence the project. For instance, it is necessary to examine the political situation, competitors, emerging technologies, legal framework and suppliers among others (Charles, 2011). Planning is the first phase within the ship acquisition process. After planning the project for investing on a vessel, different designs and models for new ships are developed (Avin, 2013), followed by a commercial phase in which the selection of the shipyard takes place through bidding processes. In this phase, some of the important factors that the ship owner must take into account are for instance the technical capabilities and experience. Finally, the production of the ship, takes place (Charles, 2011).

2.2 The transport sector in Norway

For centuries, maritime activities have been Norway's most important source of income. Historically, goods and people traveled by boats over water – on rivers, over lakes, across the fjords and along the coast. Today, Norway is one of the leading countries in marine technologies, with the offshore and aquaculture sectors constituting the two biggest industries in the country. The Norwegian merchant fleet is one of the world's largest (Monsrud, 2009), and Norwegian fisheries are exporting to all corners of the world.

There is still however significant maritime activity along the Norwegian coast. Statistics Norway estimated that in 2006, 197 million tons of goods went through domestic ports. That same year, cruise liners carried 6.2 million people ashore, while Hurtigruten (the Coastal Steamer) and other service routes saw 9 million passengers. Furthermore, car ferries transported an additional 40 million passengers (Monsrud, 2009). However, taking into account inland activities, the total domestic transportation of goods has shifted from predominantly seaborne freighting to road hauling. According to Statistics Norway, the percentage of domestic cargo transported by sea and rail has decreased significantly since the 1960's. In 2006, the same amount of goods (in tonne-kilometres) were transported by sea and road, which means that road transportation has increased nearly 30% since the 1960's, relative to other modes of transportation (Monsrud, 2009). With more goods transported on roads, the greenhouse gas emissions from this sector is increasing. According to the Norwegian Environment Agency (2014), road traffic alone accounted for 58% of the total transport sector emissions in 2012, but these also includes personal transportation. Table 2.1 gives an overview of the cargo transported by sector for 1960 and 2012.

Table 2.1: Percentage breakdown of tonne-kilometres (TKM) transported by sector. The numbers are adapted from Statistics Norway, and does not include domestic airfreight (Monsrud, 2009: 12).

Year	Sea (%)	Rail (%)	Road (%)
1960	69	13	18
2006	46	7	47

What this implies is that the greenhouse gas emission from domestic transport as a whole is disproportional between the sectors. A study by Vestlandsforskning shows that greenhouse gas emissions from road transportation is significantly higher than for sea freighting per tonne-kilometre. Figure 2.3 gives an overview of greenhouse gas emissions for different modes of transport in Norway.

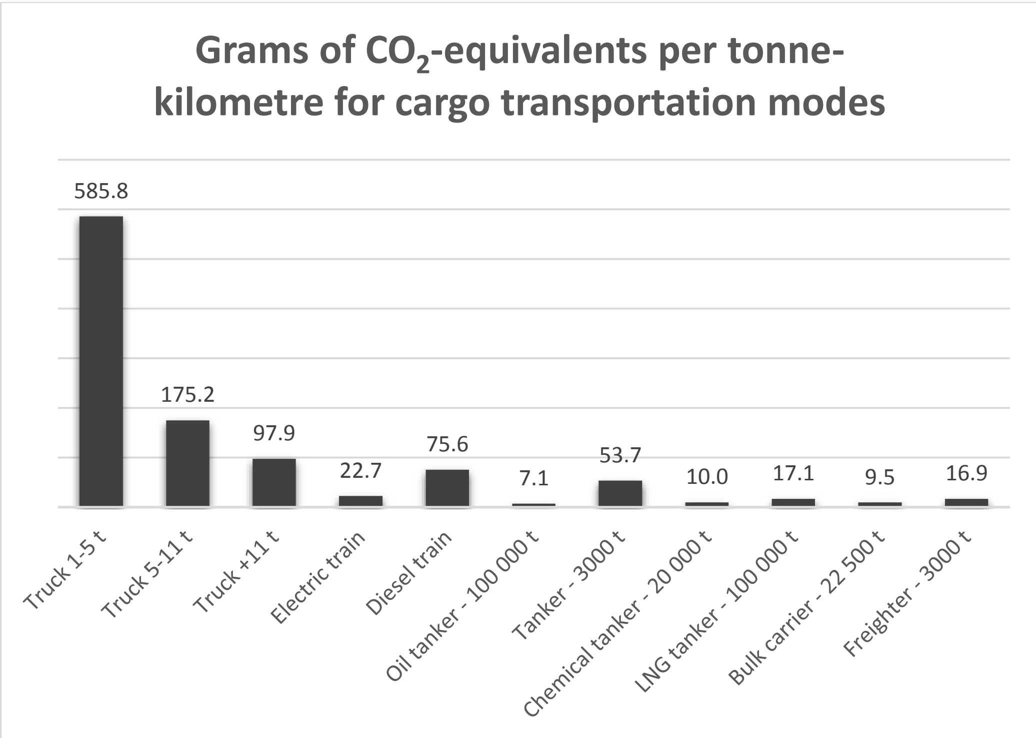

Figure 2.3: Greenhouse gas emissions by mode of transport. Adapted from Vestlandsforskning (Simonsen, 2010: 23).

2.3 Exhaust gas emissions from marine engines – NO_x, SOx and CO_2

In this chapter, the main marine exhaust gas emissions will be discussed. The content of nitrous oxides (NO_x) and sulphur oxides (SO_x) from fuel exhaust have in recent years been subject to strict regulations under MARPOL Annex VI (Kristensen, 2012). This is especially eminent in so-called Emission Control Areas (ECAs), which are special regions subject to stricter regulations on either the sulphur content of fuels or the NO_x content in marine engine exhaust. New design requirements on energy efficiency in ships are also employed to reduce the contribution of greenhouse gas emissions from the shipping industry (IMO, 2011a). Particulate matters and uncombusted hydrocarbons are not discussed in this chapter.

2.3.1 The environmental profiles of NOx, SOx and CO_2

The combustion exhaust of hydrocarbon fuel consists mainly of oxygen, nitrogen, carbon dioxide and water vapor – essentially *air*. Additionally, a small amount of carbon monoxide, sulphur and nitrogen oxides, particulate materials and uncombusted hydrocarbons are also emitted (Kristensen, 2012). This exhaust signature, as shown in Figure 2.4, is somewhat similar for most marine engines, respective to the fuel used for combustion. Some fuels, like liquefied natural gas (LNG) differs from for instance marine diesel oil (MDO) in that it contains little to no sulphur and release less nitrogen oxides.

2.3.1.1 NO_x

NO_x is the collective term for nitrogen oxides resulting from the oxidation of nitrogen found in the combustion air or fuel. Oxidation of atmospheric nitrogen, dependent on local combustion chamber conditions, will have a propensity to form nitric oxide (NO) early in the combustion cycle. Later in the cycle, a lesser amount of this will convert to highly toxic nitrogen dioxide (NO_2) and a very limited amount of nitrous oxide (N_2O) (Kristensen, 2012). NO_x emissions has a detrimental impact on the environment. The various "noxides" effect the environment differently. NO_2 has an adverse effect on respiration and vegetation, and is associated closely with acid rain. NO_x partakes in both the creation and depletion of ozone. In the lowest level of the atmosphere (the troposphere), it can interact with volatile organic compounds (VOC), creating ozone through photochemical reactions with sunlight. Ozone is known to be highly toxic to both plants and animals (Kristensen, 2012). N_2O in the atmosphere forms an extremely potent greenhouse gas with a CO_2-equivalence of 298 – meaning that one N_2O molecule has the same ability to trap heat in the atmosphere as 298 molecules of CO_2 (Forster et al., 2007). It also binds to ozone, which adds to ozone depletion (Portmann et al., 2012; Ravishankara et al., 2009).

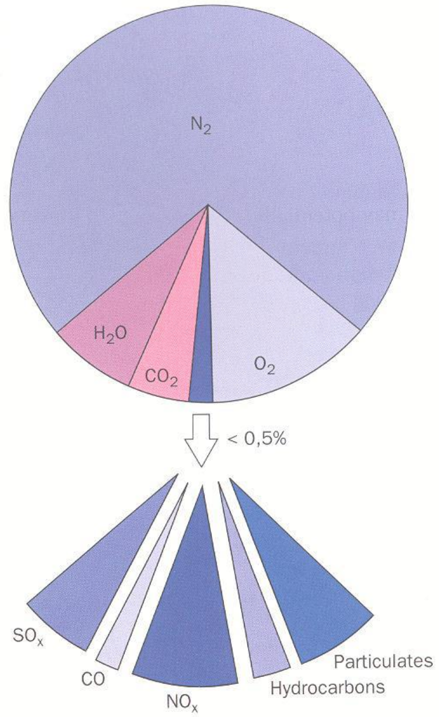

Figure 2.4: Composition of marine diesel engine exhaust emissions (Lloyds Register, 1995, in Kristensen, 2012: 5).

2.3.1.2 SO_x

SO_x are oxidants of sulphur contained in the fuel, with the amount of sulphur in MDO varying as much as 4.5% globally to 0.1% according to specific area regulations (Kalli et al., 2009; ECG, 2011). The sulphur oxidants found in the exhaust are primarily sulphur dioxide (SO_2), and to a lesser degree sulphur trioxide (SO_3) (Kristensen, 2012). SO_x, together with NO_x, are the primary causes for acid rain (Goedkoop et al., 2009), and cause adverse health effects to human respiration, vegetation and building materials (Kristensen, 2012: 6).

2.3.1.3 CO_2

In environmental discourse, carbon dioxide (CO_2) is a well-known greenhouse gas (GHG) and is the principal unit of measure for Global Warming Potential (in CO_2-equivalents). The radiative forcing – the budget of incoming solar energy and heat radiated back from the earth – depends very much on the atmospheric concentration of CO_2. The concentration of carbon molecules has a much higher propensity to reflect infrared, long wave radiation, than shortwave radiation (in the form of visible light). Visible light from the sun passes through the atmosphere and heats up the earth. As the heat radiates from earth in the form of infrared light, some is reflected back from atmosphere. CO_2 also interacts with the oceans, dissolving into carbonic acid (H_2CO_3). In the ocean, carbonic acid has an effect on the pH concentration through disassociation of H^+ ions.

Thus, CO_2 is necessary to life on earth. It is necessary for photosynthesis, and it is integral in regulating the climate. The increasing emissions of CO_2 from the combustion of fossil fuels greatly contributes to the atmospheric concentration of the molecule, which has a significant effect on global warming.

2.3.2 Regulations on marine exhaust gases

This subchapter presents the principal regulations concerning the three main emission types described above. The legislative measures presented are all subject to the International Convention for the Prevention of Pollution from Ships (MARPOL), which is the main international convention on marine pollution prevention (IMO, 2014a). The convention contains regulations that are aimed at preventing and minimizing accidental and operational pollution from ships. MARPOL includes six technical annexes, one of which deals specifically with air pollution from vessels. The Annex VI, Prevention of Air Pollution from Ships (entered into in force from 2005), sets limits on NO_x and SO_x emissions for marine engine exhaust. In certain special regions, so-called Emission Control Areas, more stringent standards on NO_x, SO_x and particulate matters are applied (IMO, 2014a).

Recently included (from 2011) in Annex VI is a new mandatory technical and operational efficiency measure, aimed to greatly reduce the greenhouse gas emissions from the shipping industry. This is further explained in 2.3.2.1 below.

2.3.2.1 CO_2 - Energy Efficiency Design Index (EEDI)

The International Maritime Organization (IMO) recognize that the worldwide maritime traffic has an effect on the global climate, due to increasing GHG emissions. Currently, maritime transport represents 3.3% of the global CO_2 emissions, but this number is expected to rise drastically (150%-250%) by 2050 (Lindstad et al., 2012).

In the latest amendments to MARPOL Annex VI *Regulations on energy efficiency for ships*, the Energy Efficiency Design Index (EEDI) becomes mandatory for ships over 400 GT (IMO, 2011a). The EEDI sets a requirement for a minimum energy efficiency level per the capacity (e.g. tonne miles) for the different ship sizes and types. This is calculated by a formula based on the ships technical design parameters, giving a specific figure for the ship category in grams of CO_2 per tonne miles (IMO, 2011b).

New ship designs will have to meet the EEDI requirements, which are tightened every five years to keep up with new technology. The first phase started in 2013, requiring a CO_2 reduction level (CO_2/tonne mile) of 10%, from a baseline calculation from ships built between 2000 and 2010. This will rise to 30% towards 2030 (IMO, 2011b).

2.3.2.2 NO_x and SO_x – Emission Control Areas (ECAs)

Some areas subject to sea traffic are due to oceanographic and ecological reasons defined by MARPOL as "special areas". In these areas, special consideration to the prevention of sea pollution is made mandatory (IMO, 2014c). Table 2.2 gives an overview over these areas.

Table 2.2: Special areas under MARPOL. Adapted from IMO (2014c).

Annex VI: Prevention of air pollution by ships (Emission Control Areas)	In effect from
Baltic Sea (SO_x)	19 May 2006
North Sea (SO_x)	22 Nov 2007
North American (SO_x, and NO_x and PM)	1 Aug 2012
United States Caribbean Sea ECA (SO_x, NO_x and PM)	1 Jan 2014

In Europe, these special control areas regulates the sulphur content of marine fuels, called Sulphur Emission Control Areas – SECAs. Currently, the sulphur content, by mass of the fuel, is limited to 1% in SECAs and 3.5% under MARPOL globally. From January 1st 2015, this will be lowered to 0.1% and 0.5% respectively.

In NO_x ECAs, marine engines are controlled through Engine International Air Pollution Certificates (EIAPP). Depending on the build year, the NOx exhaust output from marine engines must conform to the respective tiers, as presented in Table 2.3. The actual limit value in the specific tiers are calculated from the rated engine speed (RPM). In Tier III, the emission limit factor would be $9 \times (n^{-0.2})$, where n is the rated speed. For an engine rated at 750 RPM, the maximum allowed NO_x content would therefore be 2.4 g/kWh (IMO, 2014b).

Table 2.3: NO_x control requirements of Annex VI for Tiers I, II and III. Modified from IMO (2014b).

Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)				
Tier	**Ship construction date on or after**	**n < 130**	**n = 130 – 1999 (750)**	**n ≥ 2000**
I	1 January 2000	17	12.1	9.8
II	1 January 2011	14.4	9.7	7.7
III	1 January 2016	3.4	2.4	2

2.4 Technologies in meeting regulations

In chapter 2.3.2, regulations on the environmental impact of marine fuel were introduced. As members of the IMO, Norway and the EU are obliged to follow these international regulations. This is especially true for the Nordics, with the North Sea and Baltic Sea pertaining to the IMO's Emission Control Areas for sulphur. As previously mentioned, the limit for sulfur content in marine fuels will drastically diminish from 2015 – especially in SECAs. Thus, new and different engine and fuel technologies, and ways to control the combustion process will play a greater part once the stricter rules enter force (Kristensen, 2012). To be able to comply with the coming SECA regulations, two measures can be taken for the shipping industries in these areas; changing the fuel technology, or implementing exhaust abatement measures for existing fuel technologies. The fuel alternatives that can fulfill the 2015 SECA regulation are low sulphur fuels (LSF) and LNG.

In the case of maritime propulsion technology, the selection of available technology alternatives are on the contrary quite limited. There are altogether approximately 11 different propulsion systems available, or available in the near future (Marine Insight, 2011). Of the technologies listed in Table 2.4, the Norwegian government promotes LNG as a viable alternative in meeting current and future regulations. Among current commitments, the Norwegian government is committed to reduce NO_x, SO_x, VOCs and ammonia emissions through the Gothenburg Protocol of 1999.

2.4.1 The NOx-fund

A measure to reduce NO_x emissions comes from the Ministry of Climate and Environment through the *Environmental Agreement relating to NO_x*, together with national trade organizations (2010). As a result, in a joint effort between the *Confederation of Norwegian Enterprise (NHO)* and the government, the NOx-fund has been set up, where participant members may apply for economic assistance for NO_x reducing measures (NHO, 2014). Increasing amounts of the subsidies are given to projects that makes possible the use of LNG as primary energy carrier in both the maritime sector and land based industries. Currently, 40% of the NO_x commitments set forth by the government has been reached through LNG-projects, and the NHO estimates a 6000-ton reduction of the substance annually (NHO, 2013).

LNG is particularly attractive to the government in this respect, because of the drastically lower NO_x emissions, together with lower greenhouse gas emissions and a near 100% reduction of sulfur oxides (Nørgaard, 2013). The increasing demand for LNG, however, stresses the importance of supply infrastructure and price. This will be further discussed in chapter 2.4.2. A comparison between LNG and MDO will be presented in chapter 4.3.

Table 2.4: List of maritime propulsion technologies – description of existing and future alternatives.

Diesel propulsion	The most common maritime propulsion system. Thermal energy is released from hydrocarbon fuel combustion, which through mechanical energy conversion drives a propeller shaft. Described in detail in chapter Error! Reference source not found..
Wind propulsion	Harnessing wind power through equipping sails on vessels has had a huge significance on the maritime history. Wind propulsion is currently explored today as a future alternative, with wind turbine propulsion (Bøckmann and Steen, 2011), as well as kite- and sail propulsion for merchant shipping (see also Bøckmann and Steen, 2013).
Nuclear propulsion	An alternative to fossil-based fuel, this technology utilizes nuclear fission to produce massive amounts of energy used to power the ship – which can go years without refueling. Currently limited to naval vessels and arctic icebreakers, with only a few nuclear merchant vessels produced.
Gas turbine propulsion	Mainly naval ships. May function as a boost in evasive maneuvering when the vessel is under attack.
Fuel cell	Functioning similar to a battery, fuel cell power pack engines utilizes the chemical energy in fuels at an extremely efficient rate, converting it to electricity without combustion. The reactants are hydrogen and air, forming the anode and cathode respectively. Hydrogen for this use can be found in existing commercial fuels, such as natural gas, ethanol, methanol and ammonia (Ludvigsen and Ovrum, 2012).
Biodiesel fuel	Biodiesel is currently being tested as a possible more sustainable diesel alternative for the maritime sector. Compared to MDO, biodiesel does not contain sulphur, and has the possibility to eliminate SO_x emissions altogether. The downside is current technology limitations, making for a possible higher NO_x emission rate, together with higher cost and ethical considerations regarding food crops utilized for biofuel feedstocks (Opdal and Fjell Hojem, 2007).
Diesel-electric	Diesel-driven generators drive an electric propeller system. Today, this is generally limited to azimuth thrusters, and has thus a more restricted use (cruise ships and other vessels that require high maneuverability).
Gas fuel/dual engine	LNG is on its way to pose a very viable alternative to MDO and LFO. LNG does not contain sulphur, and has a reduced NO_x and CO_2 emission profile compared to conventional fuel oils. Thoroughly described in chapters 2.4.2 and 4.4.1.1.
Excluded technologies	• Coal-fired steam propulsion • Solar generated propulsion • Water-jet propulsion These technologies are either not in use, outdated or not applicable in this context.

2.4.2 LNG – the market, demands and security of supply

In this chapter, LNG and its feasibility as a new technology is presented.

2.4.3 What is LNG?

Liquefied natural gas, LNG, is a liquefied natural hydrocarbon gas mix used for power generation. The gas is primarily made up of methane (85-95%), with lesser amounts of other hydrocarbons like ethane, propane and butane (Statoil, 2014). When liquefied, the gas takes up about 614 times less volume than in its natural, gaseous state, which greatly increases storage capacity. When liquefied, the gas can be transported and utilized without the need for a pipeline infrastructure. This makes LNG a very flexible alternative, in that markets where the use of natural gas exceeds the indigenous production, such as Europe and the US. In such instances, LNG can be supplied from other areas according to demand, where commercial terms are more competitive (Grønhaug and Christiansen, 2009).

The transformation process from natural gas to its liquefied state is done by cooling down the gas at atmospheric pressure to $-162^{\circ}C$ (Grønhaug and Christiansen, 2009). This is done at the liquefaction plant. From there, the LNG is shipped in specially built LNG carriers to large tank farms in buyer countries. These carrier vessels can hold from 145,000 to 200,000 m^3 of liquefied gas, which is the equivalent of up to 1.4 TWh of energy – enough to supply the annual electricity demand for 50,000 Norwegian households (Statoil, 2014).

2.4.4 LNG in the maritime market in Norway

The Norwegian gas market, which used to be dominated by a select few companies, is now expanding. The sale of LNG has in recent years increased significantly, primarily due to governmental pressure for environmentally friendly ferries and coastal guard services, as well as subsidies for LNG projects from the NOx-fund (NHO, 2013). Based on tighter maritime regulation on emissions and applications for support from the NOx-fund, the NHO estimates a 17% increase in the consumption of LNG fuel by 2016 – compared to a 7% market share in 2011 (Figure 2.5).

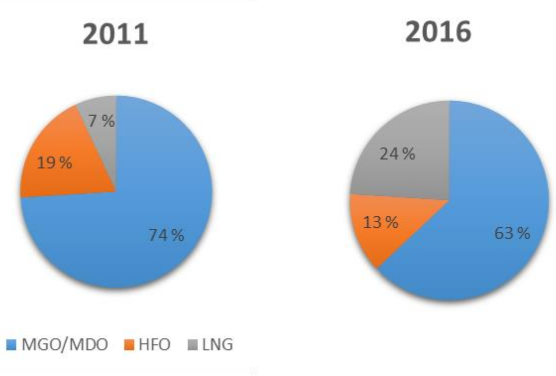

Figure 2.5: Fuel sales in Norway for maritime use, 2011 and (expected) 2016. MGO/MDO = marine diesel, HFO = heavy fuel oil, LNG = liquefied natural gas. From DNV, in NHO (2013: 6).

Based on numbers from DNV, NHO expects the sale of LNG is expected to increase drastically. This development is believed to be caused by the NOx-fund, which is not exclusive to the maritime industry. In 2011, the industries (production and manufacturing) and mining sector consumed 83220 tons of LNG. In comparison, the maritime transport sector consumed 50370 tons. The demand for LNG – especially from the maritime sector – is expected to increase almost exponentially towards 2016, as shown in Table 2.5. A side effect of this is a decreased cost of the distribution of LNG, due to the much higher volume of LNG traded. Det Norske Veritas (DNV GL) estimates as much as a 30% cost reduction in LNG distribution in Norway, based on the 2016 market outlook (NHO, 2013).

Table 2.5: Trends in LNG sales in Norway, 2004 to 2016 (NHO, 2013: 7).

LNG sales, 2004	*2011*	*2016 (expected)*
28470 tons	145000 tons	400000 tons
	+ 509%	+ 1405%

Consequently, DNV deems the financial support from the NOx-fund crucial in making LNG an economically viable option for both the maritime and manufacturing industries in Norway (NHO, 2013). The LNG development is thus currently carried economically by the fund, which again is tied to the Environmental Agreement relating to NOx. Follwing EU regulations, this agreement is to expire in 2018 (2013). By 2017, the NOx-fund will cease the subsidies, meaning that a decline in the price for LNG and associated costs must be in order to retain further growth in the Norwegian LNG market. The Norwegian Research Council concludes that the high cost level for natural gas in Norway is primarily due to "a lack of transparency and competition in the industry, in a small market with few buyers and sellers, and a poorly developed infrastructure" (NHO, 2013: 16; from Forskningsrådet, 2012).

2.4.5 Increasing demand for LNG

In 1998, the world's first gas powered ferry, the M/F Glutra, was set afloat in mid-Norway. Five years later, Norway got another world first with the first LNG powered offshore supply vessel (NHO, 2013). These are not singular events, but rather a part of a trend in the Norwegian maritime industry, cementing its place as an industry leader in maritime LNG technologies. LNG as a viable technology is growing, 40% of ships operating with – or changing to – LNG are found in the offshore sector (NHO, 2013). NHO (2013) suggest in addition to governmental regulations and international pledges to environmental goals, expected fuel price increases on marine fuel might also contribute to the increasing interest in LNG in other maritime industries – such as the domestic shipping industry.

With an expected increase in the use of the technology, there is undoubtedly a great future demand for LNG, as seen in Figure 2.5 and Table 2.5. To secure this progress, there must therefore be a supply to meet the demand. To meet the 2016 estimation of 400 000 tons of LNG, NHO presents the Melkøya facility in Northern Norway as a possible measure in filling this need. Imports from already established and new LNG terminals in Europe are seen as possible measures, but may be subject to demands from increasing LNG efforts by the EU (2013). This concern is also voiced by Shortsea Shipping (Haram, 2014). According to Shortsea Shipping, the LNG demand is expected to rise up to 2-4 million tons a year in 2020. Even with a larger coverage of vessel filling stations, this will not be sufficient to supply the growing market. In such, the expected volume of LNG will not be the problem, but rather the infrastructure from which it can be distributed.

3 Methodology – Systems engineering in Multi-criteria decision analysis

In this chapter, the systems engineering theory is reviewed. Additionally, Multi-criteria Decision Analysis (MCDA) is studied in order to illustrate how these methods can contribute to the decision-making process, as decisions are made over a life cycle perspective, and influence the results and outcomes of the projects during the different life cycle stages.

A specific MCDA method, the Analytic Hierarchy Process (AHP), is selected to obtain the preferences of the decision maker. The AHP is further explained in chapter 3.4. Following the introduction of MCDA model types, applications in the transport sector are listed in order to identify the most applied methods, and to discern which criteria that have been used in other studies. The relation between MCDA and systems engineering is presented, and from this analysis, an approach to structure decision problems is proposed.

3.1 Systems thinking

Systems theory describes the system as a subject and its surroundings as a whole, and how system elements interact. The structure of the system is given by the relation between the subsystems and elements. In life cycle perspective, the SE can be used to formulate, analyze and interpret the elements of the system in each life cycle phase (Fet, 1997). Bertalanffy gives the definition of a system as “a set of elements standing in interrelations” (2009: 55).

There are different types of systems. These can be classified as conceptual, physical, natural, man-made, open, closed, static and dynamic systems. The conceptual systems are based on the flows of information or ideas between the elements of a system while the physical refers to real components that are observable, measurable and occupy a volume in the space. The natural systems are those involving existing natural processes while the man-made systems, as its name says, are those produced by individuals. There is a close relation between these two last systems due to each of them has an impact on the other. Open systems interact with the surroundings while closed systems do not. Lastly, dynamic systems are changing, and imply activity and movement. On the contrary, static systems do not change and have no movement or activity. It is also possible to find combination of these types of systems, then generating integrated systems (Fet, 1997).

In order to design a system, Blanchard et al. (1990) describes a feedback sequence illustrated in the following figure:

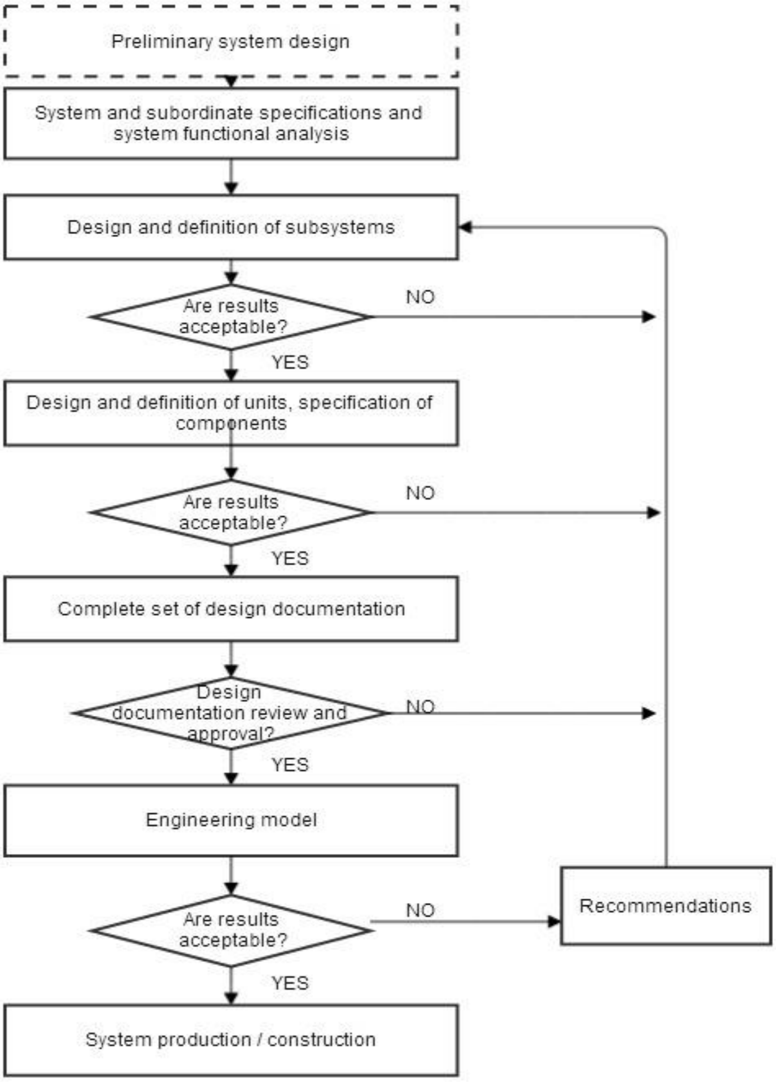

Figure 3.1: Basic design sequence. From Blanchard et al. (1990)

Figure 3.1 illustrates a simple sequence of the design system process containing feedback flows of information to improve the design until an adequate model of the system is developed and can be implemented. The system has to be delimited accordingly to an objective and function, regulating the elements inside the system.

In this study is important to identify how the alternatives, the different technologies of the propulsion systems of vessels, can influence the level of performance of the most important aspects (criteria) and consequently the selection of a specific type of vessel. Environmental and economic information of the technologies and fuel types within the system is required for the decision process. This study will concentrate on the operational phase of the ship in order to contribute to identify the preferences among the alternatives and establish the criteria for the selection of the ship.

The systems engineering methodology consists of a process that contributes to identify the requirements of the system, their implementation, verification of the implementation of the requirements and a feedback for improvement (Fet, 1997). This process follows six steps as shown in the following diagram:

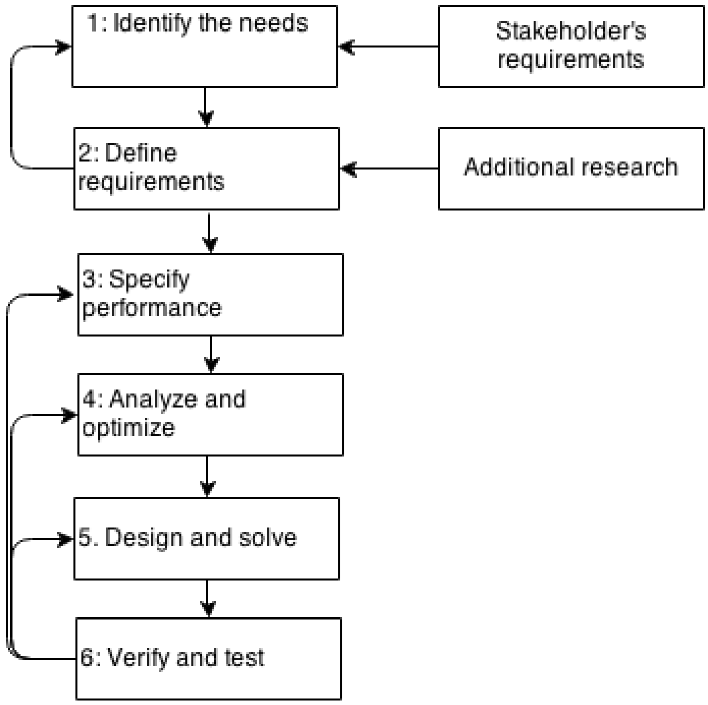

Figure 3.2: Systems Engineering Methodology. From Fet (1997).

The first step is to identify the needs. It is necessary to determine the requisites of the client or stakeholder, the reasons why are they wanted and search for possible solutions on how the needs can be fulfilled.

The second step is to define the requirements for the system. All elements in the system have functional, operational and physical necessities. These are requirements to accomplish what is wanted (functional); requirements related to the actions to operate the system (operational); requirements of the physical means necessary to connect all the elements and subsystems within the system, determining how the needs are going to be satisfied (physical).

The third step is to specify performances. This means that the requirements must be converted into measurable quantities and considered all over the life cycle of the activities in the system. The measurements are used to verify the requirements (Fet, 1997). In this section, the functional approach is useful. The functional analysis consists of the identification, description and relation of the functions of a system in order to meet the needs.

The fourth step is to analyze and optimize. At this point the evaluation of different alternatives or solutions to the needs takes place. The performance needs to be measured establishing the criteria, conditions of measurements and the objective function for the evaluation of the system. Independent evaluation of parameters in the system contributes to assess the alternatives.

The fifth step is to design and solve. An interdisciplinary design team should be established and the subsystems and elements should be defined in detail to fulfill the requirements/needs recognized previously.

The last step is to verify and test. The system should be tested to verify that the required performance is satisfied.

3.1.1 The systemic relations of decision elements

As will be further elaborated in chapter 3.4.1 below, decision problems can be structured into three parts; the problem, criteria to characterize the problem and alternatives that fulfill these criteria. This is the linear structure of a decision problem; however, decision processes are seldom linearly solved. If viewed as a system, the problem, criteria and alternatives makes up system elements (or sub-systems). They interact with each other, and permeate the system boundary to react with the systemic environment – the *decision context*. Figure 3.3 gives a graphical presentation of the systemic nature of a decision process. The relation between systems theory and MCDA will be further explored in chapter 3.5.

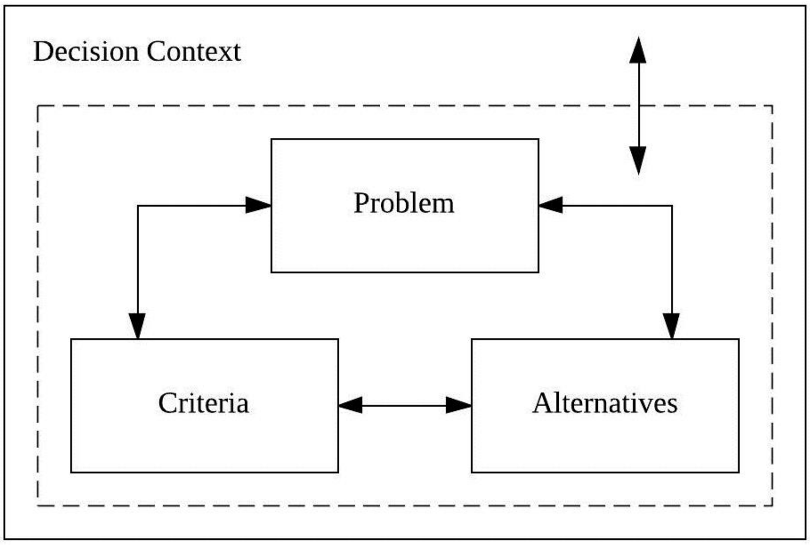

Figure 3.3: System representation of a decision process.

3.2 MCDA

Multi-criteria Decision Analysis (MCDA) is a group of approaches on decision evaluation methods and used for structuring problems, which help individuals or groups to make decisions, considering several criteria. This tool combines objective measurements and the subjectivity of the decision makers. MCDA helps decision makers to understand and structure the problem, recognize the trade-offs and select the most preferred option (Belton and Stewart, 2002). According to Belton and Stewart (2002), the MCDA process consists of three phases (problem structure, model building and action plan) which are described below. Figure 3.4 illustrates the MCDA process.

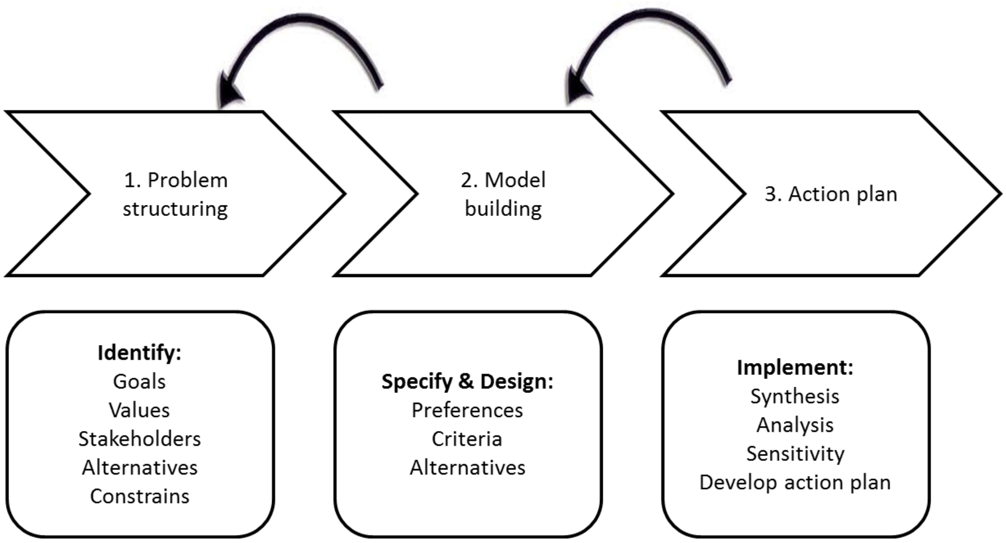

Figure 3.4: Multi-criteria decision process.

Problem Structure: in this phase all the ideas about the problem and the corresponding solutions are discussed. All stakeholders must get a common understanding of the problem and the criteria to be considered at the moment of evaluating the choices. The following information has to be defined during the structuration of the problem:

- Stakeholders
- Goals
- Constrains
- Alternatives
- Values
- Key issues
- Uncertainties

Model: in this phase a model of the preferences of the decision makers is developed. There are three basic types of models that will be introduced further on; these are value measurement models, aspiration or reference level models and outranking models. Even though, there is no specific classification for the MCDA methods. Different authors express different forms of classification (Sen and Yang, 1998).

There are three important procedures to be completed during this phase, following Belton and Stewart (2002) MCDA process:

- Specifying the alternatives
- Defining criteria
- Eliciting values

Action plan: in this phase occurs the implementation of the results of the previous phases. The implementation of the model through the development of an action plan. The following activities are included during this final stage:

- Synthesis of information
- Sensitivity analysis
- Robustness analysis
- Creating new alternatives

3.2.1 Two important definitions in MCDA:

Alternatives can be defined as the options, choices or actions that can give solution to the decision problem. In MCDA, alternatives are evaluated according to different criteria.

The *criteria* are then defined as values, objectives, attributes, key factors or characteristics inherent and relevant to the alternatives (Belton and Stewart, 2002). In this study, *criteria* is used.

3.2.1.1 Alternatives and criteria: illustrative example

The concepts of alternatives and criteria can be illustrated through the following example. Suppose there is a company specialized on building vessels. Due to environmental regulations, the company has as an objective to reduce the emissions to the air in the following vessel to be built. The alternatives or possible choices considered by the ship owners are: a) to change the propulsion system from diesel fueled to LNG fueled or b) to use abatement technologies adding scrubbers. In order to evaluate which of these alternatives is the best to give solution to the problem, a set of criteria must be identified. The criteria that can be used in this example are 1) emissions to the air; 2) costs and 3) technical properties of the ship. Since the objective is to reduce air emissions and to build a ship in accordance to the regulations, this criterion can be disaggregated into sub-criteria such as NOx emissions and SOx. In addition, the ship owners can be very interested in the investment required to make possible this project. Therefore, the cost criterion can be also disaggregated into NVP (net present value) and investment cost. The challenge for the ship owners is now to select between two alternatives and to evaluate these options among two criteria (aggregated) and four sub-criteria (disaggregated).

3.2.2 MCDA models

3.2.2.1 Value measurement models

In these models, a numeric value is assigned to determine the level of preference among the options. A value must be associated to each option; therefore, the most preferred option can be identified. The value or more specifically the value function for each alternative V(a), necessarily defines an order in the preferences. This means that preferences are complete and that follow the transitivity property. In the first place, completeness means that if there are two options to be compared, one of them is necessarily more preferred to the other one or both are equally preferred. Secondly, transitivity is explained as follows. Suppose three alternatives a, b and c, that are to be compared. If a>b and b>c, then a>c. In the value theory, the measurement of the relative importance of the criteria, taking into account their level of performance, is accomplished by creating for each criterion *i*, a partial value function $\upsilon_i(a)$ (Belton and Stewart, 2002).

The additive model is the simplest one of the value measurement models and describes the value function in an additive form, determining the overall value of an alternative $V(a)$ through the addition of the products between the score of performance $v_i(a)$ of a criterion i and the weight assigned w_i to the importance of the criterion i. The additive model can be illustrated through the following equation (Belton and Stewart, 2002):

$$V(a) = \sum_{i=1}^{m} w_i v_i(a)$$

The Analytic Hierarchy Process (AHP) is one of the most commonly used methods in value theory for multi-criteria decision analysis. This method is able to consider both subjective and objective information, but it has to be carefully used, in order to avoid inconsistencies, promote the complete understanding of the concepts by the stakeholders and to obtain the correct preferences from the decision makers.

3.2.2.2 Aspiration or reference level models

The initial focus of this method, according to Belton and Stewart (2002), is to look for optimization, considering the best performance of the most important criteria. This method is not normative and is considered "goal programing" due to the satisficing or reference levels are previously defined as goals. In the first place, the decision maker has to prioritize or organize the criteria according to an order of importance. The most important criterion is evaluated for each of the alternatives until a satisficing level of performance is reached. After selecting the criterion with the best performance, all the remaining alternatives are eliminated. Secondly, the decision maker evaluates the second best criterion against the remaining alternatives. The alternative with the highest evaluation is selected and the others are eliminated. This process is repeated for the lasting criteria.

This method is commonly used when it is not possible for the decision maker to provide all the information in a very detailed level as in the value theory method. This approach is simple and intuitive for obtaining the preferences of the decision maker (Belton and Stewart, 2002).

3.2.2.3 Outranking models

Outranking models can use cardinal or ordinal scales to establish the preferences of the criteria. To use this model, as a requirement it should exist preference independence among the alternatives. This means that the alternatives can be ranked in one criterion without any influence of the performance of other criteria. Outranking models are based on the concept of dominance. Dominance occur when the preference is evaluated for two alternatives *a* and *b*, and their corresponding preference functions (value of the preference) are $z_i(a)$ and $z_i(b)$ for a criterion *i*, if $z_i(a) > z_i(b)$, then *a* is preferred to *b*. This means that "alternative a outranks alternative b" (Belton and Stewart, 2002: 107).

In order to distinguish the outranking model from the value theory, it is important to underline two aspects. In the first place, the preference is based on the evidence. The evidence of the preference is conclusive that one alternative is preferred to another. Also, there is assumed to be enough evidence to state that "*a* is at least as good as *b*" (Belton and Stewart, 2002: 107). Secondly, when an alternative does not outrank the other one, it does not mean that both have the same value of preference or that they are indifferent (Belton and Stewart, 2002).

3.2.3 MCDA applications

Multi-criteria decision analysis and its several methods have been applied in different fields. In the transport sector MCDA has been used for evaluate projects (Machairs, 2007) due to the growing interest of MCDA application and the importance of including other criteria in the decision process, different than the costs. MCDA can also be used in the assessment of environmental impacts, coping with a large number of decision makers and depending on local, regional or global scales (Neste, 2013).

Since this document focus on maritime transport and more specifically, on the selection of a type of vessel from the ship owner's perspective, a reduce number of scientific papers during the review were specifically suitable, in order to find the use of MCDA models in the transport sector and particularly what has been done in the maritime sector. To illustrate what has been found in the literature related to multi-criteria decision analysis and the transport in the maritime sector, in Table 3.1 and 3.2, a list with the reviewed papers is presented. The tables contain the title of the document, the criteria used during the study and the type of model that was selected.

Most of the MCDA models found in the literature, specifically for the transport industry, were value theory methods (approximately 70%), from which the Analytic Hierarchy Process model was the most common. Around 50% of the MCDA transport studies reviewed in Table 3.1, use the AHP. This model has been used for the assessment of road transport projects, selection of modes of transport and vessels, and for optimization. There are only few studies related with transport specifically in the maritime sector, reason why it is highlighted the importance of making research in this field, in order to understand how decisions are made in the maritime cluster, how they can be improved and to apply useful decision tools during the process.

Table 3.1: MCDA applications to transport.

Title	Author	Method	Propblem/topic
Comparative assessment of road transport technologies	Streimikiene et al.	The interval TOPSIS method	Road Transport: assessment of transport technologies
Fuzzy Multi-criteria decision-making approach for transport projects evaluation in Istanbul	Ertugrul et al.	Fuzzy Delphi, Hierarchical distance-based fuzzy MCDM	Selection of transport alternatives: Infrastructure/mode of transport
Methods of multi-criteria decision analysis within the road projects like an element of the sustainability	Tille, Gilles	Electre III	Sustainable road projects
Multi-criteria analysis in transport project evaluation: an institutional approach	Brucker et al.	AHP analytic hierarchy process	Assessment of road transport projects
Measuring The efficiency of a ship fleet	Carpace and Cedeño	PROMETHEE	Ship efficiency in bulk carriers
Multi-criteria analysis in shipping investment evaluation	Rousos and Lee	AHP analytic hierarchy process	Evaluation of different types of ships, optimization
Modelling of a Closed Loop Maritime transportation system with Discrete Event simulation Multi-criteria Decision Analysis	dos Santos et al.	Combination of Discrete Event Simulation and MCDA	Maritime transport systems scenarios
Intelligent decision support for effectively evaluating and selecting ships under uncertainty in marine transportation	Wibowo and Deng	Fuzzy MCDA, multi-attribute utility theory, degree of dominance, degree of optimality	Maritime transport: determine overall performance of ships
A fuzzy analytic network process based approach to transportation mode selection between Turkey and Germany: A case study	Tuzkaya and Önüt	Fuzzy analytic network process (ANP)	Transport mode selection
A combined AHP-PROMETHEE approach for selecting the most appropriate policy scenario to stimulate a clean vehicle fleet	Turcksin et al.	AHP - PROMETHEE	Select policy scenario to stimulate the use of more sustainable vehicle fleet
Composite decision support by combining cost-benefit and multi-criteria decision analysis	Bruhn et al.	CBA-AHP	Transport projects: cost and strategic assessment
Multi-criteria decision-making support tool for freight integrators: Selecting the most sustainable alternative	Simongáti, G.	Aggregation with SAW, PROMETHEE	Sustainable modes of transport
Evaluation and selection of the ship collaborative design resources based on AHP and genetic and simulated annealing algorithm	He, Z. et al.	AHP, Hybrid algorithm of genetic and simulate annealing	Resources for ship design
Ship selection using a multiple-criteria synthesis approach	Xie, Xinlian. et al.	Utility function, Evidential Reasoning approach (ER)	Ship selection

The list of criteria is variable and ample; nevertheless, it was found that in general, the most common criteria are economic, environmental, technical, risk, social and policy factors. From the 14 studies selected for the review, the economic criterion is present in 85% of the studies, acknowledging its level of importance among the decision makers. The technical aspects are also present in most of the studies (approximately 64%). The environmental factor is present in 7 of the studies, as shown in Table 3.2. Finally risk, social and policy aspects are considered in some of the studies.

Table 3.2: Common criteria in MCDA studies for the transport sector.

Criteria	*Number of studies*
Economic	12
Environmental	7
Policy / regulations (internal or external)	4
Technical / physical performance	9
Risk	5
Social	5
Other	3

Table 3.3 shows the number of studies in which different sub-criteria were found during the review. The total costs and the operational costs were the most common criteria among the studies. In the case of the environmental aspect, air emissions are the most common to be included in decision processes when environmental considerations are taken into account due to the operational phase of the cases. Technical performance is commonly measured in terms of capacity or efficiency.

Each criterion and/or sub-criterion depends on the way the problem was structured. Therefore, it is possible to find for instance, in the social criteria, some measures or notions of risk or the risk can be perceived as a cost factor; subsequently, the way a factor (criterion) is defined and aggregated, is relative to the decision maker’s thinking. Thus, the classification and aggregation of criteria should not be completely generalized.

These findings were the base to develop and propose a list of criteria for the case study in this document. Also, the literature presents combination of the MCDA models.

Table 3.3: Sub-criteria considered in MCDA studies in the transport sector.

Criteria	Sub-criteria	Number of studies
Economic	Total Costs	8
	Operational costs	4
	NVP	3
	IRR / payback period	2
	Feasibility	2
	Capital costs	1
	Other costs	2
Environmental	Air emissions	4
	Life cycle air emissions	2
	Visual Impact	1
	Natural Resource Use	1
	Emissions to water	1
Policy / Normative related (public and private)	Suitability to master transport plan	1
	Dependence of foreign countries	1
	Constrains	1
	Public policy	2
	Sociopolitical acceptance	1
Technical / physical performance	Capacity	4
	Time	3
	Efficiency	3
	Technical feasibility	2
	Ship age	1
	Speed	2
	Traceability	1
	Distance	1
	Performance	1
Risk	Safety	3
	Price / cost risk	2
	Risk of causing pollution	1
	Weather conditions	1
	Machinery failure	1
Social	Competences	2
	Accessibility	2
	Comfort	1
	Risk of accident during operation	1
	Impact on society	2
	Public opinion / Media	1
Other	Reliability	1
	Equipment	1
	Appearance	1
	Automation	1

3.3 Selecting an appropriate MCDA method

Other authors such as Sen and Yang, 1998 suggest a framework for application of the different types of decision models, classifying them according to the information that is required to input in the model. The following figure represents the classification of multi-criteria decision-making methods, summarized by (Sen and Yang, 1998).

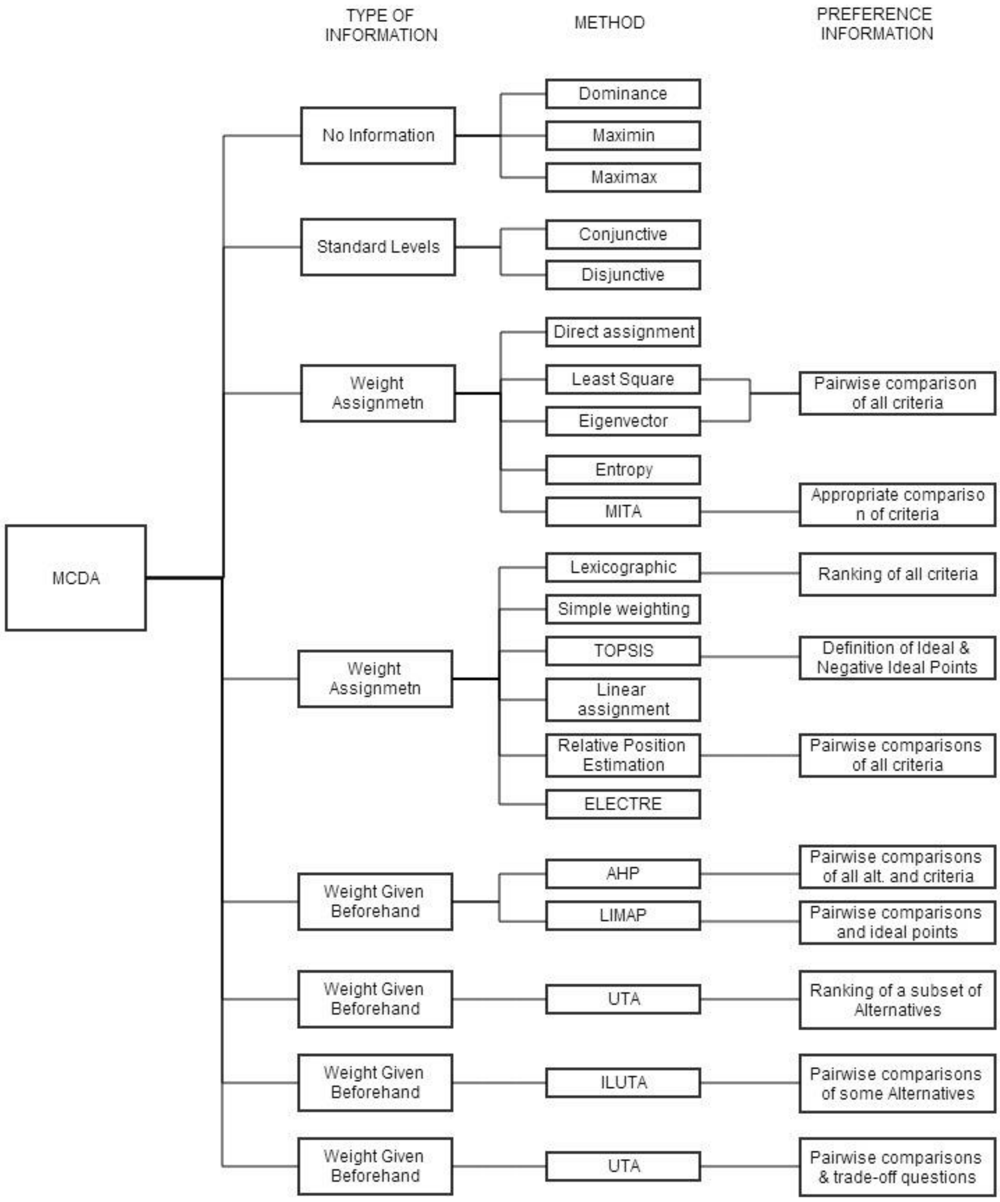

Figure 3.5: MCDA classification Methods. From Sen and Yang (1998).

Since different information is required for each model, the selection of the later depends on the preference data. There are some rules that can be followed to reach a good selection of the model. In order to achieve this, Sen and Yang (1998) proposed a decision tree for selecting the method. This decision tree is illustrated in the following figure:

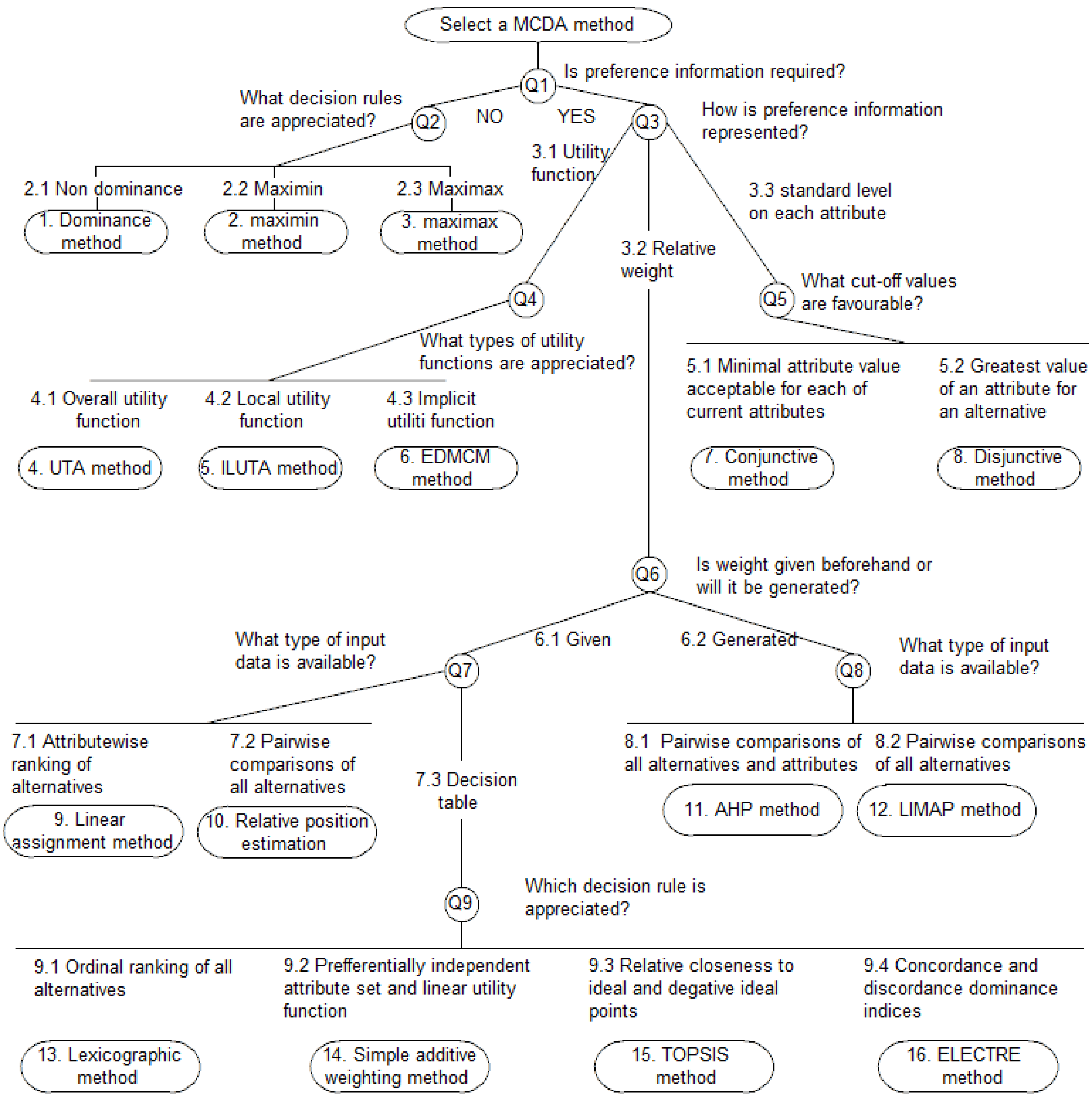

Figure 3.6: Selection of methods in multi-criteria decision analysis. Adapted from (1998: 27).

The decision tree gives guidance to select a MCDA model accordingly to the information that is available in the decision problem. However, it is also possible to use a combination of the methods with the purpose of solving or structure the problem.

Figure 3.6 was helpful for this study with the intention of selecting an appropriate method for analyzing decision-making. The method carefully chosen for this study is the Analytical Hierarchy Process, AHP. The preference information for the study was required and generated through a survey in order to compare and weight the alternatives and criteria. The implementation of the AHP will be described within the case study.

3.4 AHP: the Analytic Hierarchy Process

The Analytic Hierarchy Process is a method used in multi-criteria decision support. The AHP method deals with hierarchical structures of the criteria (Sen and Yang, 1998). Through this method, it is possible to identify the criteria and the alternatives to be considered in the potential solution of a decision problem. More specifically in AHP, the evaluation of the alternatives against the criteria considers both subjective and objective information in order to determine the preferred option among the alternatives.

The AHP method was selected from other MCDA methods due to its simplicity, flexibility and concern of objective and subjective aspects considered by the decision maker in a problem. This method compares and evaluates both the criteria and the alternatives. It is a very simple and intuitive method, in which one evaluation only requires the decision maker to express the level of preference between two options of criteria using a scale. However, there are usually a large number of pairwise comparisons required during the evaluation, which must be completed by the decision maker. It is also important to note that this method checks the consistency of the responses of the decision maker through a consistency index.

3.4.1 The hierarchical structure:

The AHP allows aggregation and organization of the criteria and alternatives in a hierarchical manner in order to facilitate and identify the concerns of the decision makers. This hierarchical organization is also called "value tree" (Belton and Stewart, 2002). The *first level* of the hierarchical structure corresponds to the overall goal of the decision problem (Sen and Yang, 1998). For instance, the goal can be to hire a person in order to perform and specific task, or to select a mode of transport, or to select a vessel to purchase. The decision pursuits the most preferred solution.

The *second level* in the hierarchical structure consists of the decision makers, the criteria and sub-criteria considered in the problem (Sen and Yang, 1998). There could be only one decision maker or several. This depends on the context and the interested parties with enough power of decision. For instance, two decision makers in a project can be the government and the representatives of the private sector; also, the decision maker in a project can be only the owner of the company. In addition, in the second level of the decision tree, the criteria and sub-criteria must be listed. As mentioned before, the criteria are the important aspects relevant to the goal. If the objective is to buy a car, common criteria to select a car would be safety, cost and comfort. Moreover, sub-criteria encompass specifications of the criteria. If it is necessary to consider different aspects inside the criteria, these can be broken down. For instance, if you are evaluating the safety of the car, you might disaggregate this criterion into number of airbags and the breaks system, resulting in two sub-criteria. Notice that it is not necessary to have sub-criteria for all the criteria.

According to (Dodgson et al., 2009), it is important to state that the number of criteria must be as low as possible but large enough to contribute to a well-grounded decision. There is no specific amount of criteria to justify the decision in the problem; however, an average range of criteria for typical cases is from six to 20 criteria. This corresponds to the consideration of completeness to ensure that all important criteria are included, apprehending all the significant aspects of the objectives and disregarding the unnecessary factors.

Finally, in the *third level* of the hierarchical structure, the alternatives take place. When selecting a car, alternatives can be for instance Skoda or BMW, according to the brand of the cars.

The general hierarchical structure is illustrated in Figure 3.7.

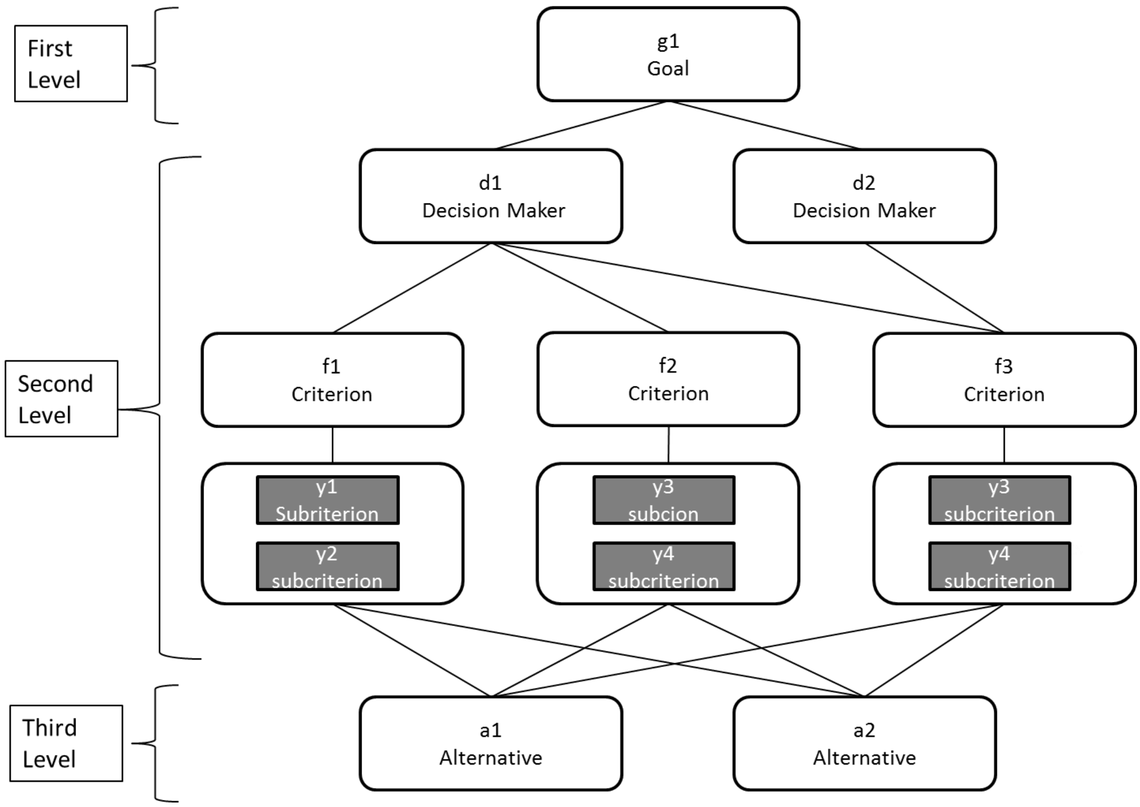

Figure 3.7: Hierarchical structure.

3.4.2 Axioms and considerations in AHP criteria:

There are four basic axioms on which the AHP methodology is based. These are 1) the reciprocal axiom, 2) the homogeneity axiom, 3) the synthesis axiom and 4) the expectation axiom (Forman and Gass, 2001).

Reciprocal axiom: In a pairwise comparison, an element A is X times more important than element B. This is A=XB. This axiom states that the reciprocal of this equation is also true. This is A/X=B. For instance, if A=3B then, B=A/3.

Homogeneity axiom: the elements being compared in a segment of the hierarchy should not have large differences in their properties. This can reduce consistency errors.

Synthesis axiom: in the hierarchical structure, the elements do not depend on others in lower levels of the hierarchy.

Expectation axiom: ensure an adequate representation of the ideas of the decision maker in the hierarchical structure.

All MCDA problems must follow certain considerations when identifying and grouping the criteria. Several considerations to take into account when identifying criteria have been presented in the literature (Belton and Stewart, 2002; Dodgson et al., 2009). These considerations can be summed up to the following:

- ✓ *Value relevance*: there must be a link between the criteria selected and the value or importance that the decision maker gives to a specific criterion in order to meet the overall goal. In other words, the selected criteria have to be important (have value) for the decision maker.

- ✓ *Understandability*: Decision makers must understand the concepts in regards to the decision problem, preferences and the information to be analyzed, in order to avoid conflicts and undesired results.

- ✓ *Measurability*: criteria must be measurable in order to be compared against the alternatives, and measure their level of performance.

- ✓ *Redundancy:* criteria should not be redundant. It must be checked if there are duplicates or irrelevant criteria not relevant to the goal. It is wise to look over if different criteria are measuring a same factor. If necessary and if there is enough information, a correlation coefficient can be helpful to identify redundancy.

- ✓ *Completeness*: this consideration answers to the fact that all criteria relevant to the comparison of the alternatives are included. Nonetheless, the level of detail (sub-criteria) should be kept as the minimum required but capturing all the key aspects in the problem.

- ✓ *Operationality*: criteria and sub-criteria must be carefully defined in order to be assessed and to make possible the judgment of the alternatives against each criterion. This means that the model must be practical and possible to use.

- ✓ *Mutual independence of preferences*: criteria can be judgmental independent if for each criterion; the preference of an option can be scored without knowing the preference scores of the remaining criteria.

- ✓ *Size (simple/complex):* high level of specification might lead to large numbers of criteria and at the same time, this implies a huge effort to assess the information and communication can become very complicated.

3.4.3 The method description

This MCDA method is similar to the multi-attribute value function (MAVF), used for eliciting the value function (Belton and Stewart, 2002). AHP takes into account, both objective and subjective sides of a decision problem, expressed by the decision makers (Saaty, 1980). After identifying the levels in the hierarchical structure, pairwise comparisons between the levels (criteria and alternatives) are performed. This process is completed through the eigenvector method. With this technique, the elements can be ranked (Sen and Yang, 1998) and the preference weights can be adjusted to be comparable. The eigenvector method is used to determine the vector of priorities with the relative weights from the comparison matrix and to check the consistency of the preferences by obtaining the eigenvalue (Saaty and Vargas, 2001).

3.4.3.1 The scale and comparison matrix

Since the method is based on pairwise comparisons for scoring the criteria and weighting, it employs ratio scales to measure the preferences. The numerical evaluation of the alternatives is given by the responses of the decision makers to the questions of the pairwise comparisons (Belton and Stewart, 2002). In the first place the criteria to be considered and the possible alternatives are determined. For each criterion a pairwise comparison between the alternatives is to be made. This comparison identifies the level of preference between the alternatives in each criterion through a numerical scale. According to Belton and Stewart (2002) and Saaty (1980), the scale of preference represents the following values:

Table 3.4: Preference scale.

1	Equal preference
3	Weak preference
5	Strong preference
7	Very strong preference
9	Absolute preference

After all the comparisons are done, the values are inserted on a pairwise comparison matrix A. This matrix is a squared matrix labeled the rows and columns with the elements of comparison. The elements in the comparison matrix represent the importance of one criterion relative to another. In general, an element a_{pq} represents the importance of the pth criterion relative to the qth criterion in the matrix and it will be located in the pth row and the qth column as shown in Figure 3.8. If the element a_{pq} is greater than 1, then the pth criterion is more important than the qth criterion. Due to the reciprocal axiom it is valid to state that $a_{qp} = {}^{1}/_{a_{pq}}$, as shown in Figure 3.8.

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1q} \\ a_{21} & a_{22} & \cdots & a_{2q} \\ \vdots & \vdots & \vdots & \vdots \\ a_{q1} & a_{q2} & \cdots & a_{qq} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1q} \\ 1/a_{12} & a_{22} & \cdots & a_{2q} \\ \vdots & \vdots & \vdots & \vdots \\ 1/a_{1q} & 1/a_{2q} & \cdots & a_{qq} \end{bmatrix}$$

Figure 3.8: Comparison Matrix

Now, an example is introduced in order to explain how comparison matrices are elaborated. Consider three criteria to select a car: safety, cost and comfort. Assume that criterion p is safety; criterion q is the cost and criteria r is comfort. Then, the decision maker evaluates the criteria in the following order, using the values in the scale of preferences:

- Safety is weakly preferred to costs ($a_{pq} = 3$)
- Costs are absolutely preferred to comfort ($a_{qr} = 1$)
- Safety are equally preferred to comfort ($a_{pr} = 9$)

The comparison matrix in this example will be as follows:

$$
\begin{array}{cccc}
 & \textit{Safety} & \textit{Cost} & \textit{Comfort} \\
\textit{Safety} & 1 & 3 & 1 \\
\textit{Cost} & 1/3 & 1 & 9 \\
\textit{Comfort} & 1 & 1/9 & 1
\end{array}
$$

Figure 3.9: Example comparison matrix.

3.4.3.2 The eigenvector method

The eigenvector is a technic used to weight and adjust assignments. This way of eliciting the preferences is very simple, using pairwise comparisons between the criteria. A comparison matrix is made in order to identify how strong the preference for one criterion is in comparison with other. This means that the values inside the comparison matrix represent how many times a criterion is more important or preferred (Sen and Yang, 1998). The eigenvector solution is used to determine the vector of priorities from the comparison matrix and also to evaluate the consistency of the preferences of the decision maker (Saaty and Vargas, 2001). According to Sen and Yang (1998), the eigenvector is the one able to satisfy the following equation:

$$W_2 = bW_1$$

Where b is the eigenvector for the elements in the second level, W_1 is the weight at the top value in the hierarchical structure and W_2 is the weight vector in the second level. The b vector corresponds to the normalized eigenvector of the comparison matrix.

In order to compute the vector of criteria weights it is necessary to normalize the matrix of comparisons (Saaty, 1980). Each entry of the normalized matrix is computed by:

$$\bar{a}_{pq} = \frac{\bar{a}_{pq}}{\sum_{r=1}^{x} a_{rq}}$$

Then, the vector of weights using the average of the rows in the normalized comparison matrix. Each entry in this vector is denoted by:

$$w_p = \frac{\sum_{r=1}^{x} \bar{a}_{pr}}{x}$$

The eigenvector method is an iterative process that is repeated until the pairwise comparisons of all the levels are reached. For instance, in the first place, pairwise comparisons between the criteria are made. Afterwards, pairwise comparisons of the alternatives for each of the criteria have to be performed.

3.4.3.3 Inconsistency

It is common to find inconsistencies when the comparison of the importance between the criteria. For instance, when comparing three criteria we can find that criterion A is more preferable than B and that B is more preferable to C but C more preferable to A. It is therefore necessary to establish the level of inconsistency through the calculation of the Consistency Index(Sen and Yang, 1998). This index is defined by Sen and Yang (1998) and Saaty (1980) as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Where λ_{max} is the maximum eigenvalue of the comparison matrix and n is the order of the matrix.

After finding the CI it is necessary to calculate the ratio between the CI and the random index (RI) in order to determine how good the result is. The RI values have been already generated for matrices of order 1 to 15 as show in Table 3.5. So, if the ratio between CI and RI is less than 0,1, the matrix is consistent. If the value of the ratio is greater than 0,1, the matrix is inconsistent. If the ratio is slightly greater than 0,1, the matrix is slightly inconsistent (Saaty, 1980).

Table 3.5: Random index (Saaty, 1980).

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

3.4.4 Steps of the AHP method

The AHP method can be explained and summarized following the steps bellow proposed by Sen and Yang (1998) and Saaty (1980).

- ✓ Identify the hierarchical structure of the MCDA problem.
- ✓ Formulate the comparison matrix (pairwise comparisons).
- ✓ Generate the normalized eigenvector and relative weight vector.
- ✓ Score the alternatives.
- ✓ Rank the elements based on the relative weight vector.

In all the comparisons consistency must be checked.

3.4.4.1 Rank reversal

Rank reversal can occur when deleting or introducing a new alternative to the decision problem. For instance, when including a new option to the problem it can cause the change in the rank of two of the other options that are not related (Dodgson et al., 2009). This might incur in the reversal of the rank of the alternatives. Rank reversal has been one of the issues that generate controversy in the use of the AHP method. One important fact of this method is that it assumes that the alternatives are independent, allowing the rank to reverse. If alternatives do not depend on each other, rank reversal does not take place and it is said that the rank is preserved. Likewise, the preservation of the rank also implies that the criteria functionally do not depend on the alternatives (Saaty and Vargas, 2001).

The most known weak points of the AHP are the required preferential independence between the criteria, possible redundant comparisons of the alternatives, leading to inconsistency problems and rank reversal. In spite of these issues, the AHP can develop acceptable answers with a careful use of it, following the axioms and specific considerations of the method (Sen and Yang, 1998).

3.5 Relating Systems Engineering to MCDA

Multi-criteria decision analysis follows the same principles of systems engineering. These two approaches share common interests to solve decision problems. Engineered systems are multidisciplinary and recognize the need and the importance of relating a variety of specialties, in order for the system to work and perform an specific function (Blanchard et al., 1990). This means that multiple criteria are considered and connected as part of elements or components or even subsystems during the life cycle of the system and the relation between those factors make possible the achievement of a specific goal or purpose and also determine the limitations for the design stage of the system. Therefore, the introduction of multi-criteria decision analysis in the planning phase of projects is a contribution to the system to reach the overall purpose; however, MCDA can be applied to different stages, systems or subsystems in order to meet the needs.

The following figure identifies the correspondent phases between the systems engineering methodology and the MCDA process.

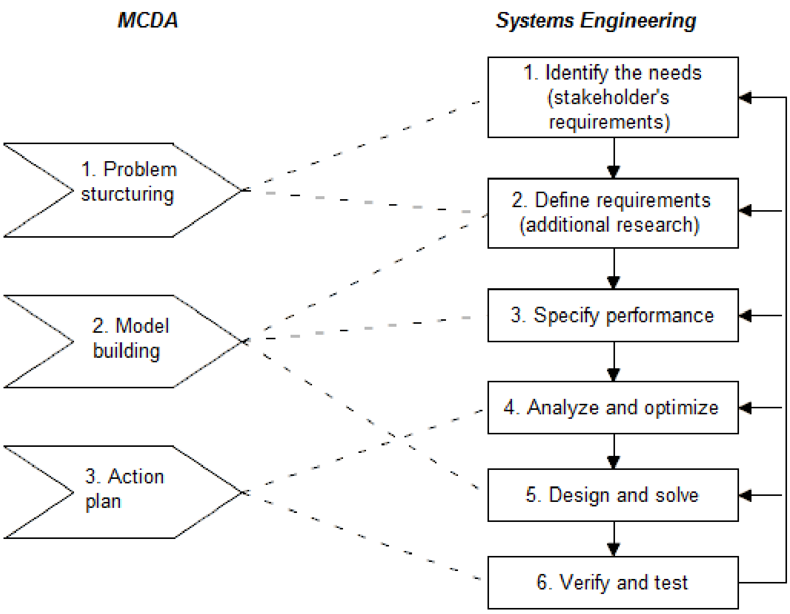

Figure 3.10: similarities between MCDA and systems thinking theory. Here, the MCDA steps identified in Figure 3.4 corresponds with the iterative steps of the systems engineering model presented in Figure 3.2.

All steps in MCDA are related and/or have similar characteristics and functionalities as the systems thinking approach. The figure below (Figure 3.11) represents our understanding on how MCDA and systems thinking theory are related, identifying the relationship between the elements in both approaches. The first stage corresponds to the identification of the needs, therefore, developing all the activities necessary to understand the problem, the requirements, what stakeholders want and possible options. Also identifying the criteria and structuring the decision problem in the system.

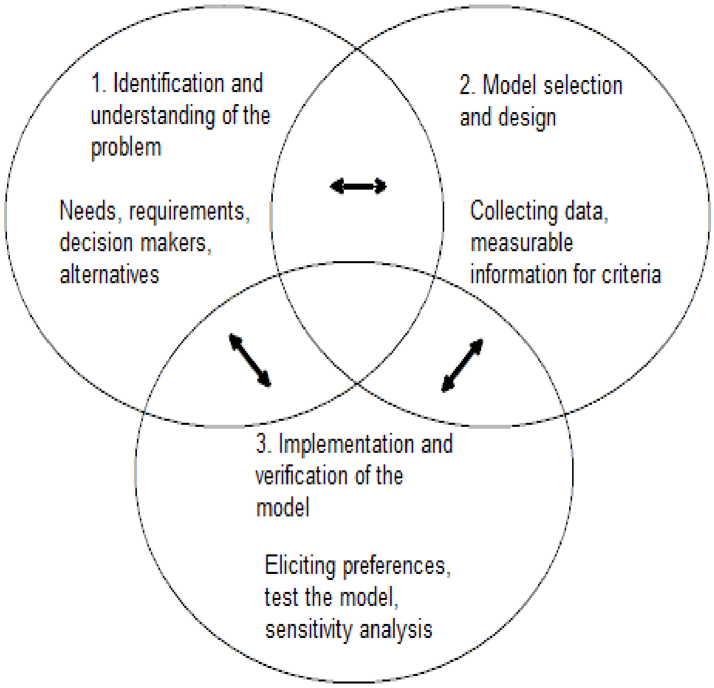

Figure 3.11: Relation between MCDA and systems engineering.

The second step designs the model in order to give solution to the decision problem, taking into account the requirements, gathering all the information in regards with all the important aspects defined in the system in measurable quantities. For last, the implementation of the design is tested and verified in a case study.

Feedback flows are always present in order to verify consistency following the steps and for making the necessary changes during the phases in order to improve the system and especially in the design phase, which highly depends on the type of information available. Feedback information is also required to verify the achievement of the goal.

3.6 Building a stepwise approach for decision support in the maritime industry

After the analysis and review of the theories in systems thinking and MCDA, a stepwise approach is proposed in this study. The purpose of this approach is to give guidance in the decision process for ship investment from the ship owner's point of view. The proposed approach integrates our understanding of the relation between the systems engineering theory and MCDA. The approach begins with identification of general and broad information, until the specific details are indicated and the approach can be tested and verified.

Systems theory presents the importance of the relation between elements or components that work together in order to meet a purpose or function. On the other hand MCDA approaches highlight the importance of taking into consideration different aspects to solve a decision problem and therefore to achieve the goal or purpose.

1. In the first step of this approach, the system is framed and systems engineering theory allows the user, in this case the ship owner, to understand the relation between several aspects and subsystems. Meanwhile, MCDA contributes to determine and delimit the system boundaries according to the interest of the ship owner or stakeholders involved in the decision process. This implies the existence of interaction among the different types of subsystems such as physical and conceptual, since MCDA considers not only quantitative information but also qualitative information (the preferences of the decision maker). This results in a more robust structure of the decision problem. In this step all the requirements, needs, stakeholders and alternatives are identified. All the interested parties in the decision problem must get a complete understanding of the system, the context, the goal and even the language to be used. Therefore, in this step, the ship owner must have a clear overview of the requirements in the systems, the aspects or criteria that are sufficiently important and interesting in order to be included, according to the purpose and system boundaries specific to the case.

2. After structuring and framing the system and understanding the requirements, a MCDA method is selected or a combination of them could be design. The selection of one or more of these MCDA methods allows the ship owner to establish and determine the preferences and level of importance of the several aspects inherent to the solution of the decision problem accordingly to the goal of the system; obtaining the most preferred option. The selection the MCDA model depends mostly on the type of information available, as mentioned in chapter 3.3. In this stage, all the detailed information is collected in the light of

the method and system requirements, finding measurable information for the criteria. The elements and subsystems are define in detail.

3. Finally, in the third step, the implementation of the model takes place through a case study, eliciting the preferences of the ship owner and the verification of it through sensitivity analysis. The information is analyzed and the alternatives are evaluated. In chapter 4, the stepwise approach is implemented to a case study on vessel investment (see Table 4.1).

4 Case study – Structuring a vessel investment using MCDA and AHP

In this chapter, a MCDA using the AHP method will be applied to a vessel investment scenario. The case will be structured using the combined SE & MCDA approach proposed in chapter 3.6. The aim of this case study is to use these frameworks to evaluate and rank two maritime propulsion technologies according to the values held by a decision maker, and the expert judgment of the authors. The scenario is based on a real life acquisition of two new LNG-powered vessels at Egil Ulvan Rederi AS, a Norwegian ship owner and case company in this study.

4.1 Case company background

Egil Ulvan Rederi AS is a small ship-owning firm located in Trondheim in Mid-Norway. The history of the firm stretches back some 95 years, transporting seasonal cod from Northern-Norway to townships further south. In the off-season, they would transport cargo. Today, the company owns and manage three cargo vessels – and has been working closely with the fish farming industry for a number of years.

In 2014, the company is set to launch two new fish feed vessels sailing for Marine Harvest. To date, these will be the world's largest feed vessels, each with a capacity of roughly 3000 tons. This project proved innovative in several other aspects as well. One of the more important requirements from Marine Harvest was a focus on the environmental performance, which would reflect their effort in environmentally friendly conduct. Essentially, this meant that Marine Harvest was prepared to incur a higher cost to increase the environmental performance. A LNG based propulsion system was in that respect the natural choice. Another innovation was fitting load- and discharge systems for the fish feed that were previously only used on shore.

When offered the project, Ulvan Rederier already had a suitable design ready. Of its nine employees, two are de facto ship owners – both former captains. Thus, in the eyes of the ship-owners, what sets them apart from larger ship owning companies is their approach to ship design. For Ulvan Rederi AS, the process of designing ships, drawing up specifications etc., is based on an overarching principle of whether or not this would be something the ship-owners themselves would captain. Their ideas, together with the specifications from Marine Harvest, were taken to Multi Maritime, a ship design and engineering consultancy, for further development on the design, before beginning the hull construction at Fiskerstrand Verft.

4.2 Establishing the decision context – description of goal, scope and boundaries

This subchapter provides the background and context necessary to establish and model the decision problem. Establishing the decision context is much like formulating goal, scope and system boundaries in a formal analysis. The decision context is formalized in Table 4.1, based on the SE & MCDA approach outlined in chapter 3.6.

4.2.1 Aim and outcome of the study

The principal outcome of this case study is an analysis on how formal decision aid tools such as MCDA and AHP can be used to evaluate and rank technology alternatives in a maritime vessel investment. This study was made possible from, and will contribute to, an overarching current project on sustainable ship production.

As previously mentioned, the study will build on Ulvan Rederi AS' investment in two new LNG vessels, but it will not necessarily be a backtracking of the original decision. Primarily because it is a decision already made, and the position here is not to assess whether or not the decision made was *good* or *bad* in any respect. Secondly, the original decision process was much larger and more complex than what can be encompassed in this thesis. When taking into account the several decision makers in the original decision undertaken, the *problem formulation* of the decision would in all probability be different – thus altering the decision context in itself.

What can be taken from the Ulvan Rederi acquisition case is a perfect opportunity to elicit preferences from a decision maker who has invested in new technology, as well as considerations on criteria, which may not have been considered or even thought about on the practitioner side of the table. After all, the tacit and explicit knowledge held by an actual ship owner makes readily available the type of considerations that cannot easily be obtained from literature or online knowledgebase. MCDA thus helps to bring this to the formal level.

The outcome of this case study is therefore expected to be, but not limited to:

- Identification of sustainable investment alternatives in a vessel investment
- A priority ranking of these alternatives over criteria representing decision maker values
- Expert judgment in rating of alternatives for the criteria
- An environmental screening of the alternatives (see chapter 4.4.1.1).

While not an exhaustive list of aspects of the study, they provide the basis for a discussion of the usability of MCDA and AHP in a vessel selection problem, as well as grounds for discussion on LNG and its further broadening in the Norwegian maritime sector. As mentioned, it is also the intention that this shall contribute to sustainable production of ships.

Table 4.1: Structuring of the decision context and study

1 – Problem structuring	Identification and understanding of the problem
Goal formulation: What is the problem/decision What is the expected outcome	Identify and rank existing versus new propulsion technology. Outcome of study: • Identification of sustainable investment alternatives in a vessel investment • A priority ranking of these over criteria representing decision maker values • Expert judgment in rating of alternatives for the criteria • An environmental assessment of the alternatives
Scope Who and what does the study entail, and what is excluded.	Norwegian short-sea cargo shipping, for a time-period of one year.
Decision maker(s) Identify stakeholders, key personnel, decision makers and experts.	Decision maker: Norwegian ship-owner investing in LNG technology. Expert judgment: Authors of the study.
Values – optional If following value focused thinking, identify the values.	N/A
Criteria Criteria should reflect the goal formulation, and possibly the identified values.	Identified by students, revised through discussions with supervisor and ultimately the ship owner. Literature used.
Alternatives Reflects the goal, scope, decision maker opinions. Must conform to criteria.	Alternatives selected from a finite list of alternatives defined by available technologies. The alternatives were selected to reflect the goal of the study, and not from the criteria selection due to the finite nature of the available alternatives.
2 – Model building	Model selection and design
Selecting a model	AHP selected.
Data collection	Access to existing economic data from three ship-owning companies. Brief sit-down and interview conducted at one of these. Literature and data specifications on engines collected from online research and one ship owner.
3 – Action plan	Implementation and verification of the model
Eliciting preferences and rating alternatives	Pairwise comparison between (1) compound criteria and (2) between sub-criteria. Weighting done by the decision maker. Objective rating of alternatives by expert judgment – in this case the students. Data and estimates for these ratings gathered from specific data and literature (see chapter 4.4.1.1).
Testing the model	Model built and tested in the designated software to (1) make sure that there are low inconsistencies and (2) to search for flaws with an actual *live* model.
Sensitivity analysis	Performed with the software, by judging alternative scenarios with parameters compared to an independent variable.

4.2.2 Setting up the case study – system scope and boundaries

The decision to be made is a problem of technology investment in ship acquisition. Geographically, the case is set to the Norwegian coastline, with a temporal resolution of one operational year. The study includes one decision maker, and two alternatives. The system threshold of the study is defined by the model presented in Figure 4.3.

4.3 Alternatives

Alternatives, according to value-focus theory, should rise from discussions and formulation of criteria (Keeney, 1994). This is especially applicable in settings where there may be room for many alternatives, or there may be alternatives not yet considered. It is evident that not all of the technologies presented in Table 2.4 are applicable. In fact, by formulating just a few screening criteria, these alternatives can be reduced to just two. It is reasonable to state that alternatives must be:

- Applicable for small-to-medium sized vessels
  (<5000 GT, 300-1000 RPM engine rating)
- Technology must be currently available in Norway
- Available in the foreseeable future
- Economically feasible

The last natural criteria, environmental performance, is one that is explored generally in this case study through environmental criteria. A more in depth discussion on environment in MCDA can be found in chapter 5.

Subsequently, existing technologies that are *available* on the market today are essentially two types; diesel based propulsion engines and gas driven engines. HFO as a fuel technology one could argue should be included. However, it is not as common in the designated capacity category of vessels. Liquid hydrocarbon fuel is therefore represented by MDO. Biodiesel could have been included, but technology limitations and forecasts of future feasibility does not fit with the requirements for the criteria (Opdal and Fjell Hojem, 2007). If the decision context was ranking sustainable alternatives, more of the propulsion technologies featured in Table 2.4 could have been included.

Consequently, one could argue that if a value-focused approach had been taken, more of these technology alternatives could have been included formally in the final decision process. As outlined, with such an approach, the criteria would first be selected, and from these criteria, alternatives would be identified. In Figure 3.3, we show that the decision context, problem, criteria and alternative selection contains elements of interplay, in which the elements – if viewed as sub systems – interacts and shapes the outcome of the others. This study is no different, and as provided in chapter 3.5, forms an iterative process. The primary selection possible alternatives have been selected independently from the criteria. Finally, the decision context is related to the case study background – and thus, the alternatives from the case are naturally represented in the MCDA model presented in this study as well.

4.3.1 Description of engine alternatives

The alternatives presented in this study are modelled after two vessels in the Ulvan Rederi fleet, corresponding to the chosen fuel technology alternatives, marine diesel oil (MDO) and liquefied natural gas (LNG) propulsion. Table 4.2 gives an overview of the alternatives.

Table 4.2: Comparison of vessel alternatives. Full list of specifications are in Appendix D 1 and 2.

Vessel information		
Vessel	With Junior[1]	With Harvest/Marine[2]
Class	DNV*1A1 Reefer / Container, Ice C, E0, Nord og Østersjøfart	DNV *1A1, General Cargo Carrier, Gas Fuelled, Clean, TMON, E0
Building year	2009	2014
Main dimensions		
Length overall (o/a)	66.70 meters	69.90 meters
Length between perpendiculars (pp)	61.70 meters	68.40 meters
Beam	14.60 meters	17.20 meters
Moulded depth	10.82 meters	8.60 meters
Gauge summer	5.25 meters	6.50 meters
Deadweight tonnage	2040 tons	3300 tons
Gross Tonnage	2363 GT	3250 GT
Machinery		
Main engine	ABC 8 DZC-1000-173-A, 1840 kW	Rolls Royce C25:33L9P, 2360 kW
Propeller (tilt), diameter	3.2 meters	3.8 meters
Service speed (knot)	12.5	13

[1] Egil Ulvan Rederier AS (2014a), [2] Egil Ulvan Rederier (2014b)

The following is a brief description of the engine alternatives. To compare between the alternatives, it is necessary to establish the specific energy demand requirements for the engines, i.e. the specific fuel oil consumption (SFOC) (Kristensen, 2012), in order to calculate fuel consumption and emissions from combustion of the fuel. In this study, this is limited to the main engines used for propulsion and generation of electrical power. Auxiliary engines and other motors are not included in this study. The engine alternatives in this study are medium speed, four stroke engines rated up to 1000 RPM.

Marine Diesel Engine System

In this study, the MDO alternative is modeled after the Anglo Belgian Corporation (ABC) DZC class diesel engine, used in With Junior (Anglo Belgian Corporation, 2001). It is a 4-stroke, medium speed engine with a RPM rating between 720-1000, with an 1840kW effect at full RPM.

SFOC at 1000 RPM:

191 g/kWh, for marine diesel or gas oil (MDO and MGO) with a net calorific value of 42.7 MJ/kg.

The complete datasheets is available in appendices C1-C2 and D1.

Figure 4.1: With Junior. Courtesy of Olav Neerland, Moen Slip AS. From Multi Maritime (N.D.).

Lean Burn Gas Engine

The LNG alternative is modeled after the Rolls Royce Bergen C26:33L lean-burn gas engine (Rolls-Royce, 2012b), as no specification sheet for the Rolls Royce C25:33L9P engine was available at the time of the study. Both engines are a part of the Rolls Royce Bergen engine class system, with similar specifications. Only SFOC have been calculated from the C26:33L engine system, other specifications are taken from the C25:33L MDO/MGO engine specification sheet (Rolls-Royce, 2012a)

The engine is a four stroke, medium speed spark ignited lean-burn gas engine, rated up to 1000RPM, with a 2360kW effect.

SFOC at 1000 RPM:
7550 kJ/kWh, based on reference natural gas with a net calorific value of 36 MJ/nm^3.
Converted to more tangible units, the SFOC becomes 0.155g/kWh

Figure 4.2: With Marine or its sister ship With Harvest. Still from animation, courtesy of Multi Maritime (Egil Ulvan Rederi AS, 2014b)

4.4 Criteria

What sets a *multiple criteria analysis* apart from a so-called *mono-criterion* analysis is the ability to piece together criteria representing different angles from which the problem – or *goal* – can be approached. In a mono-criterion analysis, one criteria is carefully constructed as to consider all points of view, which is problematic, if taking into account the preferences of several decision makers (Bouyssou, 1990). The criteria presented in this chapter are selected by the practitioners and refined through discussions with the decision maker. This approach ensures that the criteria fits the context of the overarching decision goal *Vessel Investment*, presented in Figure 4.3. In this case study, the model is limited to a single decision maker. A multi criteria decision model is in this case however necessary to capture diverging interests pertaining to vessel investment. Table 4.3 gives an overview of the criteria selected in this MCDA. These are also described in full later in this chapter.

Table 4.3: Overview of criteria used in the MCDA.

Criteria	***Notation***	***Unit of measure***	***Description***
NO_x	y_1	Gram per gram fuel	
SO_x	y_2	“	Emissions to air. Gives the environmental impact of the alternatives.
CO_2	y_3	“	
CAPEX	y_4	Million NOK/yr	Capital expenditure related to vessel investment.
OPEX	y_5	“	Operational expenses associated with the operation of vessels.
Capacity	y_6	Gross Tonnage	The gross cargo capacity of a vessel.
Speed	y_7	Knots	Cruising speed of the vessel. 1 knot = 1.852 km/h.
Risk	y_8	Equipment quality	Perceived risk towards investing in new technology.

4.4.1 Air emissions

To avoid redundant disaggregation of criteria, "air emissions" is here a single criterion. The intention is to capture the decision maker's preference on "environment", without eliciting preconceptions the decision maker may hold for this particular category. While "environment" might hold several connotations relating to the term, it is inherently vague as to what is intended with the term. Depending on the context, "environment" can hold very different meanings. Although vague or non-descript criteria might help to maintain preferential independence, they should not confuse the decision maker.

If the decision maker in this case is very preoccupied with worker safety, he or she might understand "environment" as "working environment", whereas another may understand it as "environmental impact". In the case of this model and vessel investment, "environment" is intended to be understood as the environmental impact or burden directly related to the operational technology of the vessel.

One way of avoiding this potential confusion altogether, is to disaggregate into several sub-criteria representing aspects of "environment". This was done initially. However, while academics in the environmental field, such as the authors, may have no trouble discriminating between for instance "NO_x" and "SO_x" emissions, there is no guarantee the decision maker know enough to have a real preference for either. Because the decision context is vessel technology investment, it is safe to assume that the decision maker has an understanding of environmental impact of vessel operations, as well as current regulations and initiatives to which his or her company must adhere.

The main difference of the alternatives in this case is the fuel technology, MDO and LNG. The indicators that best describes the environmental performance of these technologies are found in the air emissions impact category. Emissions to air in the maritime context are generally understood as atmospheric discharges of CO_2, NO_x and SO_x from the combustion of hydrocarbon fuel. While it could be interesting to see how the decision maker ranks these in terms of importance, they should be aggregated into "air emissions" to maintain preferential independence. Because of the NOx-fund, described in chapter 2.4.1, the decision maker might intuitively think NO_x is the more important, where he or she would otherwise be impartial to either three. On the other hand, CO_2, NO_x and SO_x all contribute differently to the environmental impact of fuel combustion. It is therefore hard to combine these into a single impact category. CO_2, which is a so-called greenhouse gas (GHG) contributes to global warming, and atmospheric CO_2 acidifies the ocean. NO_x, together with SO_x, are the primary causes for acid rain (Goedkoop et al., 2009). A way to include the three as sub-criteria, while still maintaining preferential independence, is to give them an equal weighting of 1/3. Thus, the alternatives can be rated according to their actual environmental performance for these criteria, while simultaneously keeping the decision makers weighting on the "air emissions" category compared to the other compound criteria.

4.4.1.1 Environmental impact assessment of air emissions sub-criteria

The environmental effect of the alternatives will be described briefly in this chapter. The analysis will form the basis for the rating of the "air emissions" criteria with respect to the alternatives. The data is based on specific data where possible, and will be supported by literature. Data sources are listed in tables Table 4.4 and Table 4.5.

Table 4.4: Engine data for the vessels.

Vessel	***Fuel type***	***Engine***	***Used for modeling***
With Junior [1]	MDO	ABC 8 DZC-1000-173-A, 1840 kW [3]	Same
With Marine/ With Harvest [2]	LNG	Rolls Royce C25:33L9P, 2360 kW [4]	Rolls Royce C26:33L lean-burn gas engine [5]

[1] Egil Ulvan Rederier AS (2014a), [2] Egil Ulvan Rederier AS (2014b), [3] Anglo Belgian Corporation (2001), [4] Rolls Royce (2012a), [5] Rolls Royce (2012b).

Table 4.5: Specific fuel consumption (SFOC) and emission data for the engine alternatives. S = Specific data, L = Literature.

Engine type	***ABC 8 DZC-1000-173-A, 1840 kWh***		***Rolls Royce Bergen C26:33L***	
Factors	MDO	Source	LNG	Source
g NO_x /kWh	7.6	S[1]	1.3	L[2]
g SO_2/kWh	3.99	L[2]	0	L[2]
g CO_2/kWh	609	L[2]	426	L[2]
g fuel/kWh	190	S[3]	155	S[4]

[1] EIAPPC (2011), [2] Kristensen (2012), [3] Anglo Belgian Corporation (2001), [4] Rolls Royce (2012b).

Thus, the relation between the emission factors and the specific fuel consumption of each vessel determines the amount of pollutant produced per unit of fuel consumed. Following the equation $Ei = EFi \, / \, SFCj$ Where,

E = Emissions to the air of pollutant E
EFi = Emission Factor of pollutant i in g/kWh
SFC = Specific fuel consumption of fuel j in g/kWh

We get the results shown in Table 4.6.

Table 4.6: Grams of air pollutant per gram of fuel consumed for MDO and LNG.

$EFi \, / \, SFCj$	NO_x	SO_2	CO_2
MDO	0.040	0.021	3.205
LNG	0.008	0.000	2.750
Reduction of emissions by using LNG	80%	100%	~15%

In this example, SO_2 is used to represent SO_x emissions. Sulfur oxides are derived directly from the sulfur content of the MDO. During combustion, sulfur is oxidized primarily into sulfur dioxide – SO_2 –, and to a far lesser extent, sulfur trioxide – SO_3 (Kristensen, 2012). LNG contains very little, to no sulfur, which compared to MDO gives a 100% reduction in this category. Compared to MDO, LNG in this calculation presents a reduction of 80 and 15 per cent for the NO_x and CO_2 categories respectively. This is a somewhat more conservative estimate than given by Rolls-Royce for their Bergen class engines, claiming a 92% NO_x reduction and 22% reduced CO_2 emissions on their gas combustion engines compared to liquid fuel technology – including so called methane slips from uncombusted gas (Rolls-Royce Marine, 2012). Table 4.7 below gives an overview of emission reduction estimates on LNG compared to marine fuel oils currently in use. Comparing the results from this study with the average shows less than a 10% discrepancy.

Table 4.7: Percentage reduction of emissions from LNG compared with current marine fuel oils.

Source	NO_x	$SO_x \, / \, SO_2$	CO_2
This study	80%	100%	~15%
Rolls-Royce[1]	92%	100%	22%
DNV[2]	85-90%	100%	20-25%
IMO[3,4]	60%	90-100%	5-15%
Average	79.9%	98.8%	17.4%

[1] Rolls-Royce Marine (2012), [2] DNV (2010), [3] IMO (2009), [4] CNSS (N.D.)

A possible problem with using LNG is the risk of uncombusted fuel being emitted to the surrounding environment. As LNG is comprised mostly of methane (CH4), emissions of uncombusted fuel essentially means a direct emission of methane – which is a greenhouse gas 25 times more potent than CO2. According to Bengtsson et al., there is an uncertainty on the scale reported on methane slip, but has been reported to vary from 0.06 grams to 3.2 grams of CH4 per MJ of LNG fuel, depending on the engine type and load (Bengtsson et al., 2014).

4.4.2 Cost

According to Triantaphyllou and Baig, contradictions between criteria exists in most MCDA's, where typically an alternative A might be better than B for one criterion, while the opposite may be true for another (2005). Cost is a typical example, where costs in whichever form they may occur, are the limiting factor to how alternatives are preferred – i.e., how the perceived benefits weighs up against the cost for the alternative. Therefore, while MCDA may help the decision maker(s) to structure cost issues, it is important that a sensitivity analysis in conducted to ascertain how changes in the cost-benefit axis may affect the ranking of alternatives.

In this study, capital expenditures (CAPEX) and operational expenditures (OPEX) were chosen to represent the total cost of ownership (TCO) for the vessels on an annual rate.

4.4.2.1 CAPEX

In this study, CAPEX can be understood as investment expenditures, in which the ship owning company invest capital to create future benefits. Thus, capital expenses are incurred when the company (1) invest capital to create profits, or (2) to increase the value of existing assets. For a ship owner, this means either commissioning a new vessel through shipyards or second-hand purchases, or acquiring upgrades or alterations on existing vessels in their fleet.

4.4.2.2 OPEX

Operational expenditures are the continuous costs of maintaining the day-to-day operation of the company. While the CAPEX can be seen as the investment of the necessary equipment or assets, OPEX can be viewed as the opposite – the costs related to running and the work necessary to run it (Damodaran, 2010). OPEX can thus briefly be summed up as the costs related to salaries, insurance, property management, taxes and fees, legal fees, supplies and so forth. In this study, all this will approximately be the same for both of the alternatives, as they are both vessels owned by the same firm. Additionally, voyage expenses (VOYEX) are in this study included with OPEX. VOYEX is usually understood as all expenses incurred for a specific voyage. Teekay Offshore aptly describes VOYEX as "all expenses unique to a particular voyage, including any bunker fuel expenses, port fees, cargo loading and unloading expenses, canal tolls, agency fees and commission" (2013). An important distinction is whether the VOYEX costs falls to the ship owner or the customer. For offshore, fuel costs are typically covered by the customer (Brett, 2014). If the VOYEX is provided by the ship owner, the rates might be higher. In the case of short sea cargo transportation, and the case in this study, bunkering is provided by the ship owner. No data has been received, or produced, on the case company's new LNG vessels. The fuel cost is therefore assumed to fall to the ship owner. Port fees and other taxes and fees related to the voyage are usually billed the customer.

Thus, the following characteristics are identified as the main differences for the two propulsion technologies expressed as costs:

- Investment cost (CAPEX)
- Fuel cost (OPEX)

For this case study, VOYEX is therefore incorporated into OPEX. If the study was focused on the customer side, or the customer was identified as a decision maker, this merging may not be advisable. This may also be true for other MCDA's on other forms for maritime activity or short sea shipping.

4.4.3 Technical properties

The primary function of the vessels in this study is short sea cargo transportation along the coast of Norway. As confirmed by the decision maker, *speed* and *capacity* were of high importance. As previously outlined, the aim of this study is the evaluation of a vessel investment in terms of propulsion technologies. Therefore, much less importance have been placed on other technical properties for cargo vessels, such as cargo loading technology. In this case, the vessels are not comparable in that regard due to the nature of the cargo being transported (general cargo/unit loads and fish fodder). Such considerations are therefore implicit in the compounded criteria *technical properties*.

4.4.3.1 Speed

Speed is a natural quantity criterion, and is very much dependent on the performance of the propulsion system. Speed is therefore presented as a discrete sub-criterion, and is measured in nautical miles per hour (knots, abbr. *kn*). 1 kn = 1.852 km/hour.

4.4.3.2 Freight capacity

The freight capacity, together with speed, is naturally crucial for cargo transportation. This criterion is especially interesting, as there is an inherent trade-off between cargo capacity, speed and fuel consumption. Like speed, freight capacity is therefore subject to engine performance.

Gross Tonnage (abbr. GT) has been selected in this study as the measure for freight capacity.

According to the European Commission, *Gross Tonnage* (abbr. GT), has been used as the basis for port charges across the EU the last 25 years (2006), and is a volumetric measurement that encompasses the total internal capacity of the vessel. Exceptions are exempted spaces such as water ballast tanks, open forecastle bridge, stern deck, passenger cabins and so forth (IMO, 1983). Therefore, when comparing vessels with different propulsion systems, internal cargo space may differ. In such, displacement, measured in deadweight tons (abbr. DWT) may not necessarily be sensitive to this consideration.

GT is expressed in tons of 100 cubic feet (2832 m^3) to the ton.

4.4.4 Risk

Risk is very much contextually dependent. For a financial operator, risk may be defined as to not getting return on an investment – essentially losing some or all of the capital investment. In the context of offshore drilling, it could be the risk of exposing the marine environment to toxic drilling mud and tailings. In this study, risk is understood in the context of investing in new technology.

As outlined in chapter 2.4.2, there is an expected increase in demand for LNG in the years to come. A possible bottleneck in this expansion is the prospects for distribution, hinging on the development of proper infrastructure from which the LNG can be supplied. Risk could therefore, in this context, be understood in terms of infrastructure availability.

Upon collecting data from the ship owner, it was revealed that their new LNG vessels would essentially operate on somewhat fixed routes, with bunkering facilitated by the customer. In light of this new context, fuel accessibility would be an imprecise measure for technology risk. What became apparent however, were concerns regarding equipment quality. From the ship owners perspective, new technology or equipment carries elements of risks in terms of equipment malfunction and performance. The engine selection for the LNG vessels was for instance heavily influenced by the fact that this engine class was already in in use in another Norwegian vessel. Thus, selecting this engine was perceived as less of a risk from the perspective of the ship owner. The ship owner also emphasized that as a smaller company, they had to focus on quality of equipment – even if it meant higher costs.

4.4.4.1 Equipment quality

Another point was that for them, a higher investment cost ensuring good quality equipment meant less future costs – i.e., less risk of losses.

In light of this new context, risk is expressed as a single criterion: *equipment quality*.

From the review of current literature on MCDA in chapter 3, *quality* is often a criterion in itself, or appropriated into a technical criteria cluster. Because equipment quality is in fact perceived as a risk for the decision maker in this study, and it represents a risk in the context of technology alternatives, equipment quality is therefore representing risk in this study.

However, unlike natural quantity criteria such as speed or cost, the perceived risk associated with equipment quality is not naturally quantifiable. I direct rating from the decision maker has therefore been obtained for the alternatives in terms of this criterion.

4.5 Structuring the problem into an AHP model

In the following chapter, the selection of a MCDA method, data collection and model construction will be discussed.

4.5.1 Selection of MCDA model

In MCDA, problem structuring tends to become an iterative process in which the decision context, problem formulation, criteria and alternatives in one way or another helps to shape and define the others. This systemic relationship, discussed in chapter 3.1.1 and 3.5, is important in understanding the interrelatedness in establishing the MCDA problem structure. An example of this is shown in Figure 3.3.

According to Turcksin et al., AHP is likely the most widely used MCDA method for transport evaluation projects (2011). While not directly a transport evaluation project, this case study evaluates the fuel technology for short sea cargo vessels. The method is also somewhat simple in its construction and implementation, enabling transparency.

From the AHP methodology, described in chapter 3.4, the system elements are established in tiers, with the goal or problem formulated at the apex. In-between the tiers are connections, forming a network, making available comparison or rating between the system elements (tiers), and between sub-elements (sub-criteria). Thus, it is this exact ability to decompose the problem into elements, which makes AHP especially advantageous. The decomposition of complex problems together with the simplicity of the method makes AHP attractive for transport evaluation projects.

4.5.2 Data collection

The data collection in this study was done in three ways. From a preliminary problem formulation, economic data on short sea shipping from three ship-owning companies was obtained. From this data, many of the criteria were established – and in this process, the problem structure was revised several times.

Once the formal problem definition, decision context, alternatives and criteria were in place, decision maker preferences and specific technical and economic data on the alternatives was elicited from one of the ship-owning companies, Ulvan Rederi AS. Decision maker preferences were established through a supervised questionnaire (see Appendix A1-A3 for the full questionnaire).

Finally, emission and fuel specific data was gathered throughout the project from specific sources and literature (see Table 4.5).

4.5.3 Constructing and implementing the model

A final model was constructed during the collection of data, before eliciting preferences. When the system described in chapter 4.5.1 is structured in a hierarchical fashion, we get the AHP process tree presented in Figure 4.3. This *decision tree* allows the highlight of each methodological step of the decision context structuring, as presented in Table 4.1. It also allows for an easy and transparent overview of the goal, decision maker, criteria and alternatives, and how these are related in the system.

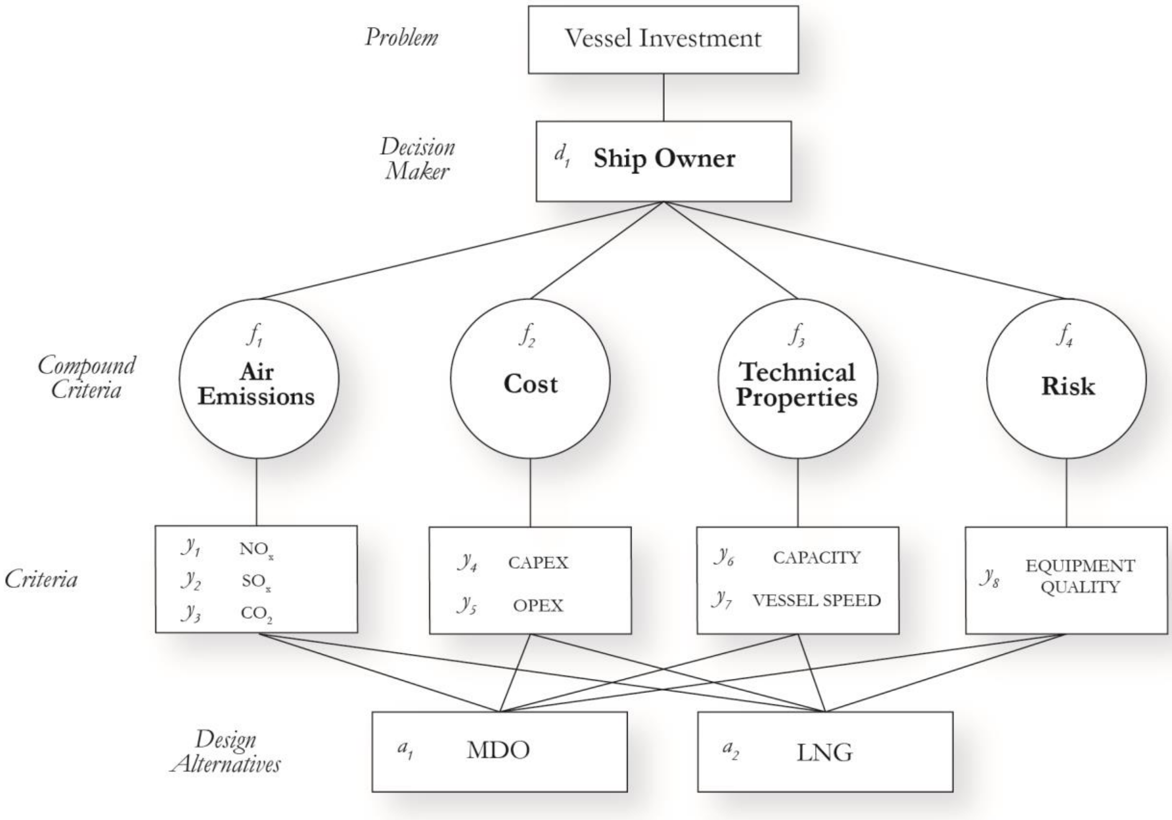

Figure 4.3: Model of the vessel investment problem using the analytic hierarchy process (AHP) tree.

In chapter 3.4, the mathematical background for AHP is explained. From this, it is clear that utilizing a dedicated AHP software helps to organize, synthetize and analyze the decision. As mentioned, the number of comparisons at each tier are $n \times (n-1)/2$ (where n is the number of criteria). Essentially, when more criteria are added, the number of comparisons dramatically increases (Aurum and Wohlin, 2006).

One approach to solve this problem is to reduce the number of criteria. In this study, several revisions on the model was done in order to reduce redundancy and superfluous criteria. The cost (f_2) sub-criteria was for instance reduced from five criteria to CAPEX (y_4) and OPEX (y_5).

For one, it reduced the number of comparisons the decision maker would have to perform, and consequently it helps to negate inconsistency and thus strengthens the robustness of the model. In total, 14 sub-criteria were aggregated to eight. It should be noted that this does not mean that important criteria have been discarded, but should be considered implicit further beneath in the structure. Maintenance costs, for instance, are aggregated into the OPEX (y_5) criterion. While it adds to the definition of operational costs, it is in itself not significant enough in responding to the top tier problem formulation of the study.

This study used the Super Decisions AHP software, developed by Saaty (see also 1980; 2001). As stated, using a dedicated software helps to structure and organize the comparisons, as well as obtaining and analyzing the results. The software also calculates the consistency index (CI) of the judgments, and enables both direct input of weights, matrix inputs as well as graphic and verbal scales for entering comparisons. Figure 4.4 shows the AHP model structure set up in the software. Since risk is only measured by one criterion, it does not need to be represented with an additional sub-criterion. The alternatives are in a separate ratings model, and are therefore not shown in the overview.

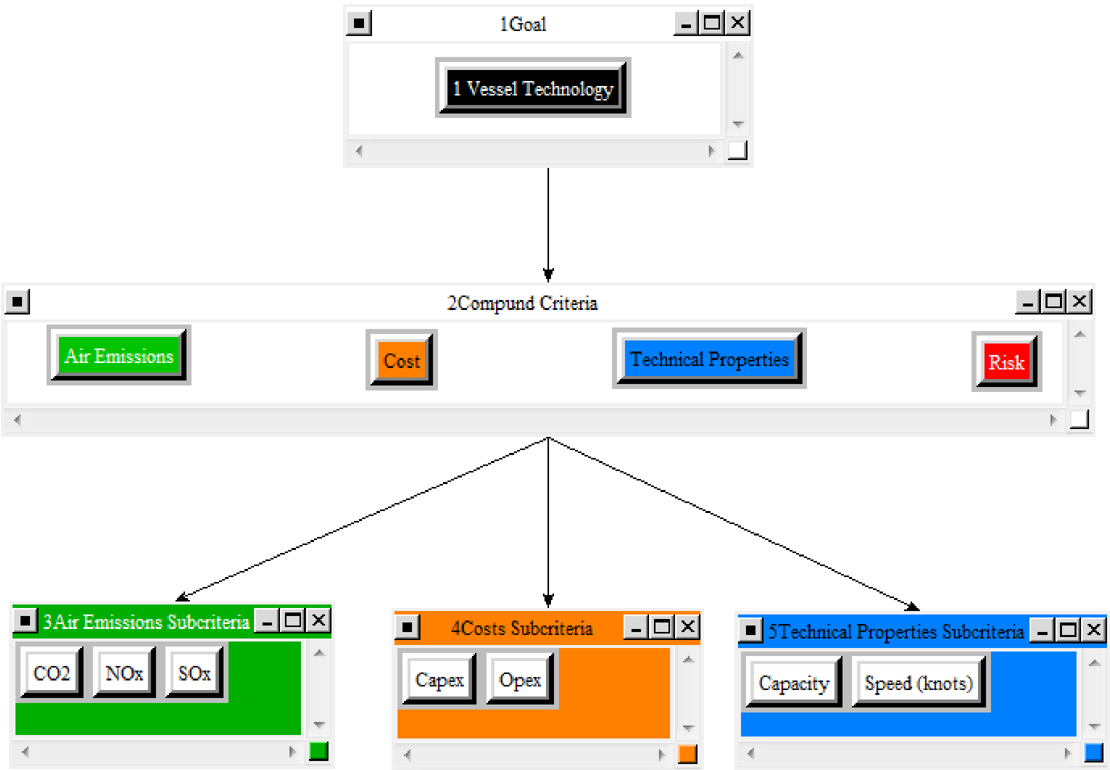

Figure 4.4: Excerpt of the model from the software.

Again, we use the pairwise comparison to *prioritize* criteria. However, to score the alternatives for the criteria, a scale is better in terms of capturing the performance of the alternative in relation to the criteria. Here, a ratings model was built in the software. The rating values were derived outside of the model (see Table 4.12). Figure 4.5 shows the complete ratings model, taken from the software.

Super Decisions Ratings

	Priorities	Totals	CO2 0.061728	NOx 0.061728	SOx 0.061728	Capex 0.032923	Opex 0.263374	Speed (knots) 0.230453	Capacity 0.028806	Risk 0.259259
MDO	0.453967	0.736877	0.861000	0.162000	0.005000	1.000000	0.521000	0.962000	0.775000	1.000000
LNG	0.546033	0.886317	1.000000	1.000000	1.000000	0.500000	1.000000	1.000000	1.000000	0.625000

Figure 4.5: Ratings model from the Super Decisions software. The numbers presented together with the criteria names are the weightings given by the decision maker. The white fields beneath displays the idealized rating score.

4.6 Weighting and scoring

4.6.1 Elicited weights on the criteria

Through a questionnaire, the decision preferences for the criteria were established. The authors supervised this process, explaining any ambiguities or misunderstandings. The questionnaire is a simple set of pairwise comparisons of the criteria, using the verbal scale presented in chapter 3.2.2.1 to elicit the weighting in each comparison. Table 4.8 and Table 4.10 shows the weighting for the compound criteria, while Table 4.11 displays the total weighted supermatrix, also showing the weighting between sub-criteria.

Table 4.8: Inconsistent comparison matrix for the compound criteria.

	f_1	f_2	f_3	f_4	*Priority*
f_1	1	1/8	1/8	5	0.140
f_2	8	1	1/7	1/7	0.171
f_3	8	7	1	7	0.506
f_4	1/5	7	1/7	1	0.183
Sum of priorities					1
Inconsistency					1.524

When the decision maker first established the importance between the criteria, the results was highly inconsistent. According to Saaty (1980; 2001), an inconsistency rating below 10% is to be considered acceptable. In this case, the rating surpassed 150% inconsistency, due to the decision maker's inconsistent ranking. While he stated that f_1, Air Emissions, was five times more important than f_4, Risk, he also stated that f_2, Cost, was eight times more important than f_1, but seven times less important than f_4. This caused a very high inconsistency rating. The authors therefore asked the decision maker to rank the alternatives according to their priority, from top to bottom:

Table 4.9: Ascertaining the priority of the compound criteria through direct ranking.

	Ranking	*Scale*		*Priority*
1.	Cost	8	8/27	0.296
2.	Technical Performance	7	7/27	0.259
3.	Risk	7	7/27	0.259
4.	Environment	5	5/27	0.185
	Total	27	1	1

The criteria are rated using the verbal scale presented earlier. Each rating is then divided on the total to get the priority (weight) for each criterion relative to the other. The decision maker stated that they are all very close in importance, but cost would be the most important. Technical performance and risk was approximately equal. Environment was also important, but were less important than the other criteria. The decision maker emphasized that in the future, environment would have a much higher importance. Table 4.10 shows the consistent comparison matrix for the criteria.

Table 4.10: The consistent and final comparison matrix for the compound criteria.

	f_1	f_2	f_3	f_4	Priority (Normalized)	Priority (Idealized)
f_1	1	1/8	1/7	1/7	0.185	0.625
f_2	8	1	8	8	0.296	1
f_3	7	1/8	1	1	0.259	0.875
f_4	7	1/8	1	1	0.259	0.875
Sum of priorities					1	
Inconsistency					0.00	

In the table, the weights are presented as normalized and idealized. When normalizing, we want to ascertain the weight of a criterion relative to the total, i.e. the importance of the particular criterion compared to the whole. We therefore normalize to one. The normalization follows the process presented in Table 4.9. In the ideal column, the criteria are prioritized in relation to the most preferred criterion – the *ideal*. The idealized priorities are obtained from the normalized priorities in the first column by dividing each by the largest. In this case, Cost gives the largest number (0.296). By dividing Air Emissions (0.185) with Cost, we get the idealized priority (0.625). The difference is thus that the normalized weights indicates how the criteria relate to the total sum, while the idealized priority column shows how the criteria rank compared to the best.

The weighted supermatrix (exported from the software) shown in Table 4.11, gives the total normalized weights for the criteria. "Goal" in respect to $f_1 - f_4$ is the compound criteria preferences, while the cells intersecting at $f_n - f_n$ are the weightings between sub-criteria y_n for a specific compound criteria f_n. Each column sums up to 1. In the final ratings model, columns f_1 to f_4 are summed to reflect their fraction of the respective compound criteria. Criteria $y_1 - y_3$ thus becomes 0.061, summing up to 0.185, which is the weighting of the compound criteria f_1.

Table 4.11: Weighted supermatrix of the criteria.

	Goal	f_1	f_2	f_3	f_4
Goal	**-**	**-**	**-**	**-**	**-**
f_1	0.185	-	-	-	-
f_2	0.296	-	-	-	-
f_3	0.259	-	-	-	-
f_4	0.259	-	-	-	-
y_1	-	0.333	-	-	-
y_2	-	0.333	-	-	-
y_3	-	0.333	-	-	-
y_4	-	-	0.111	-	-
y_5	-	-	0.889	-	-
y_6	-	-	-	0.111	-
y_7	-	-	-	0.889	-
y_8	-	-	-	-	1.000

Columns $f_1 - f_4$ gives an overview of the sub-criteria weighting. In the Air Emissions (f_1) category, all criteria are given an equal rating. Recalling chapter 4.4.1, decision maker judgment between NO_x, SO_x and CO_2 may skew the preferential independence. However, these sub-criteria are necessary to properly rate the alternatives for the air emission category, because CO_2, NO_x and SO_x all contribute differently to the environmental impact of fuel combustion. It is therefore hard to combine these into a single impact category, without losing oversight over their independent impact on the environment. Cost (f_2) and Technical Properties (f_3) have a similar division between sub-criteria, which can be attributed to little diversity in the way the decision maker utilized the preference scale. Risk (f_4) is only represented by Equipment Quality (y_8), thus giving it a weight of 1.

4.6.2 Rating (scoring) of alternatives

As shown in Figure 4.4, the ratings are calculated "outside" of the model. Setting up a separate rating model allows for evaluation of each alternative as to how it performs on each criterion. The rating of the criteria (in some literature called scoring) is done by direct rating, where the alternatives a_1 and a_2 are compared for each of the eight criteria as listed in Table 4.12. Setting up an evaluation structure like this dramatically reduces the number of pairwise comparisons needed.

Quantitative units have been selected to measure the performance of the alternatives. The criteria and their units of measurement has been thoroughly explained in chapter 4.4 above. The ratings are derived by the following equation (where higher is better):

$$\frac{a_1}{\sum_{n=1}^{\infty} a_n}$$

Where a are the alternatives. When lower numbers are preferred, for instance with cost criteria, we inverse so that the lower number gets a higher rating.

$$\left(\frac{a_1}{\sum_{n=1}^{\infty} a_n}\right)^{-1}$$

In this study, this is relevant especially for emissions and cost.

Table 4.12 gives the calculation of the ratings for the alternatives. The ratings are normalized to the total sum in each criterion, which must be done in order to compare results. The results presented in the *ideal* column are the ratings inputted to the ratings model, seen in Figure 4.5. The higher the rating, the better it performs. An ideal rating gives a good indication on the relative performance between the two alternatives. It should be noted that for the inversed criteria, such as emissions and costs, a higher rating means lower cost and emissions. Therefore, for the SO_x criterion, the correct interpretation is that MDO has SO_x emissions, while LNG emits little to none at all. Similarly, for the CAPEX criterion, LNG rates half of MDO. This is because the investment cost for LNG in this study is twice as much as for MDO.

Table 4.12: Ratings calculation.

Criteria	Notation	Unit	MDO a_1	LNG a_2	Rating a_1	Rating a_2	Ideal a_1	Ideal a_2
NO_x	y_1	gram per gram fuel	0.05	0.01	0.139	0.861	0.162	1
SO_x	y_2	"	0.02	0.00	0.005	0.995	0.005	1
CO_2	y_3	"	3.29	2.75	0.455	0.545	0.835	1
CAPEX	y_4	mill NOK/yr	6.7	13.3	0.667	0.333	1	0.500
OPEX	y_5	"	10.4	7.6	0.422	0.578	0.731	1
Capacity	y_6	Gross Tonnage	2363	3250	0.421	0.579	0.727	1
Speed	y_7	Knot	12.5	13	0.490	0.510	0.962	1
Risk[2]	y_8	Equipment quality	8	5	0.615	0.385	1	0.625

In Table 4.12, the calculation results behind the CAPEX and OPEX criteria are presented. It should be noted that it is the calculated columns that have been used, since these are calculated using the same price and emission data. As can be seen from the table, the calculated representation of With Junior differs from the actual bunkering data appropriated from the ship owner. The difference suggest that there are some flaws in the background data we have utilized to perform these calculations. The difference between the calculated fuel consumption and emissions for With Junior and With Marine is however in line with what has been suggested by the ship owner. Table 4.13 gives the SFOC for the engine outputs. The power output for the LNG alternative is derived from vessel performance simulation data from Multi Maritime given by the ship owner (Personal communication, 15.05.2014, Ivar Ulvan).

Table 4.13: Specific fuel consumption (SFOC) per kW engine output.

SFOC/kW		
Engine type	**MDO**	**LNG**
Specific fuel consumption (g/kWh)	190	155
Power output (kW)	1840	2000 (avg.)

Table 4.14: Price and emission calculation for the vessel alternatives.

Vessel	With Junior	With Jr. (Calculated)	With Marine (Calculated)
Fuel type	MDO	MDO	LNG
Unit	Liters	Liters	Sm^3
Operating time (hours/year)	-	6000	6000
Actual 2013	1600107	-	-
Calculated	-	2467764	2548200
Consumption/hour	266	411.294	424.7
Price/unit (NOK)[1]	4.2	4.2	3
Total NOK/year	kr 6 720 449	kr 10 364 609	kr 7 644 600
Price difference	0.00 %	35.16 %	12.09 %
Kg CO_2/unit	2.69	2.69	1.88
Total kg CO_2/year	4304287.83	6638285.16	4790616
Emission difference		35.16 %	10.15 %

[1] (Einang, N.D.; Enova, 2005)

Finally, it should be stressed that the calculations in Table 4.14 above are based on estimated numbers. The price per unit is an estimation from Marintek for Enova, presented in a report on natural gas trends in Norway between 2015-2025 (Einang, N.D.; Enova, 2005). There is also little literature and historical data available for LNG. Our estimation on the fuel consumption is based on a scenario with 6000 hours of operation with a static engine load. The calculated number for With Junior therefor varies a lot from the actual number given by the ship owner. In practice, the engine load is far from static. This scenario was created to ensure equal variables when comparing between the technologies.

4.7 Final rank aggregation – results and sensitivity analysis

Table 4.15 gives the final preference ranking for the model. These results show that LNG would be the best choice for the decision maker, based on the elicited preferences and expert judgment ratings. In the table, the *ideal* column shows the results divided on the highest value, so that the best alternative has an absolute priority of 1. The less preferred alternative, MDO, is then 83.1 % as good as LNG in this decision context.

Table 4.15: The final ranking of the alternatives.

Alternatives	*Normals*	*Ideal*
MDO	0.454	0.831
LNG	0.546	1

The obtained results are the decision maker's preferences formalized through the mathematical background given in chapter 3. Thus, it is the decision maker's values – the individual and the company's values and preferences. These results are in such not an entirely object assessment of the feasibility of investing in LNG for short sea cargo transportation. However, in this study, the ratings model was structured to be as objective as possible, where ratings were obtained from quantitative qualities related to the criteria. If alternative X is 40% more cost-intensive than alternative Y, then in the ratings model, this percentage gap is preserved. However, the relative importance of this cost discrepancy is modulated by the decision maker's weighting of the criteria. If the decision maker does not consider costs important compared to other criteria, then the cost difference will matter less in the final ranking of the alternatives.

In the final ranking of the alternatives in this case study, LNG is the best alternative – however, only by just shy of 17%. Looking at the ideal column in the ratings calculation (Table 4.12), we can calculate an average rating per alternative. For MDO, the average becomes 0.678, and 0.891 for LNG. The ideal becomes 0.761 and 1 respectively. In the final ranking however, the preference weightings comes into play. The environmental performance sub-criteria ($y_1 - y_3$) had for instance a very high rating for the LNG alternative, compared to MDO, but were the least preferred. Consequently, the weighting reduced the impact somewhat for these sub-criteria in the final rank aggregation. Conversely, criterion y_2 (Risk) had a better rating for MDO than LNG. Risk was also more preferred than Air Emissions for instance, and in the final ranking, this helped MDO get a higher score. This underscores the point that it is the decision maker's preferences that are of importance in MCDA – not only the head-to-head performance between alternatives.

4.7.1 Sensitivity Analysis

The sensitivity analysis (SA) is almost as important in the analysis of the study, as the results themselves. From the results described in the chapter above, we saw how the weights assigned by the decision maker influenced how the ratings model contributed to the final rank aggregation. This gives some uncertainty on the judgments made, i.e. the level of confidence we have towards the weightings. It is therefore appropriate to run a sensitivity analysis. This is also identified as a step in the model of approach developed in this study (see chapter 3.6), and is desirable for several reasons.

Principally, SA gives the practitioner the option to ascertain how the ranking of alternatives is affected by changes in criteria preferences. In essence, SA evaluates how sensitive the model is to the inputs given, and how it affects the results. This is important in ascertaining the robustness of the decision, as well as providing an overview of which criteria that are critical for the decision and identifying possible scenarios and alternative outcomes (Chen and Kocaoglu, 2008).

The figures in the following analysis shows the priority of the compound criteria plotted in the x-axis and the priorities of the alternatives in the y-axis. The sensitivity is measured in how the y-axis plots in effect to changes in the x-axis.

4.7.1.1 *Sensitivity Air emissions*

Figure 4.6 illustrates that if the preference or importance for the criterion of air emissions increases, the priority for the LNG vessel has a linear increment as well. At the same time, the preference for the diesel fueled ship decreases proportionally.

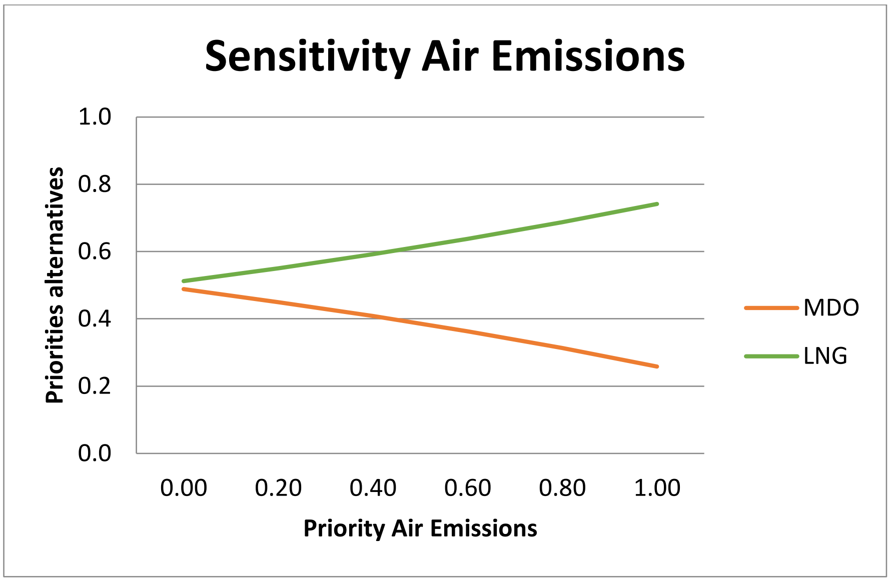

Figure 4.6: Sensitivity Air emissions

4.7.1.2 *Sensitivity Cost*

The sensitivity analysis for the cost criterion behaves in a similar way to the preference of air emissions. If the preference for the criterion of cost increases, here is an increment in the priority for the LNG vessel. The difference is that the slope in Figure 4.7 is less steep, therefore the range of preference in which the priorities varies is smaller and consequently less sensitive to the weight than the air emission. Even though, in both cases the preferred option is the LNG vessel.

The *Cost* criterion is comprised of the sub-criteria CAPEX and OPEX. In the ratings model, the CAPEX cost for MDO is 50% of the CAPEX associated with LNG, due to higher investment costs for the latter alternative. The OPEX rating for LNG is approximately 27% lower than the OPEX for MDO, as a direct result of lower fuel costs associated with LNG. In the final ranking for the *Cost* criteria, LNG received a much higher score than MDO. This because the decision maker gave OPEX a much higher priority relative to CAPEX. Thus, this priority difference amplifies as the *Cost* criterion increases, and decreases as the criterion priority subsides.

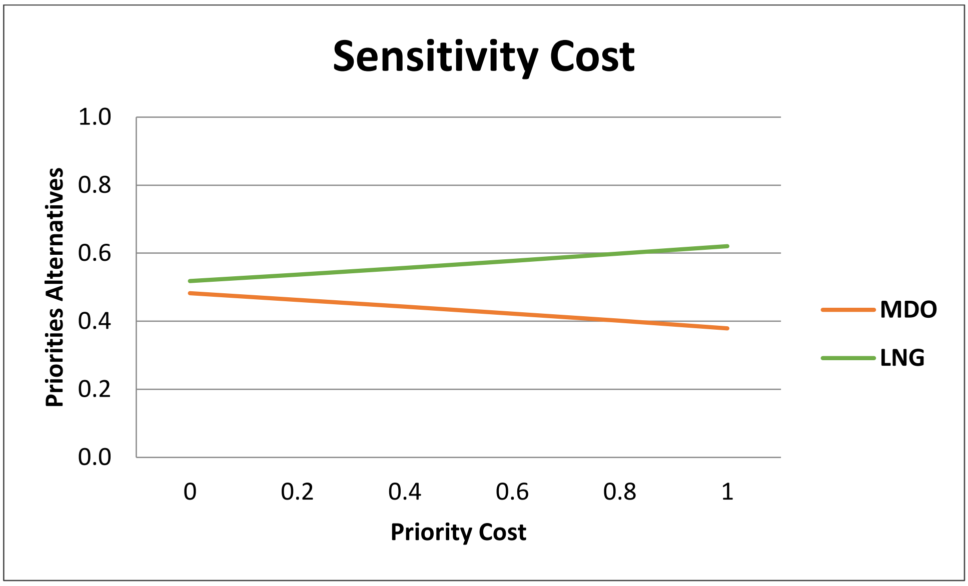

Figure 4.7: Sensitivity Cost

4.7.1.3 Sensitivity Technical Properties

On the contrary, the preference for the diesel fueled ship increases when the priority for technical properties rises and the preference for the LNG ship decreases. In any case, LNG is the preferred option for all values in the priorities for technical properties as shown in Figure 4.8.

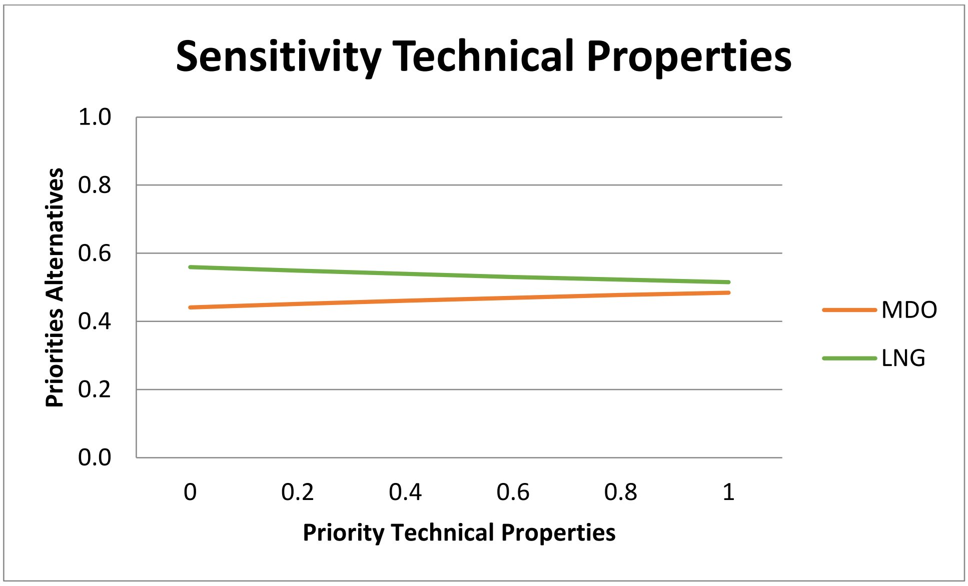

Figure 4.8: Sensitivity Technical Properties

4.7.1.4 Sensitivity Risk

In the case of the risk criterion, if it priority is greater than 0.47 as illustrated in Figure 4.9, the preferred choice is the MDO vessel. If the priority of the risk criterion is lower than 0.47, the preferred choice is the LNG vessel. This means that risk is a very important parameter that can influence the preference and final decision of the alternatives.

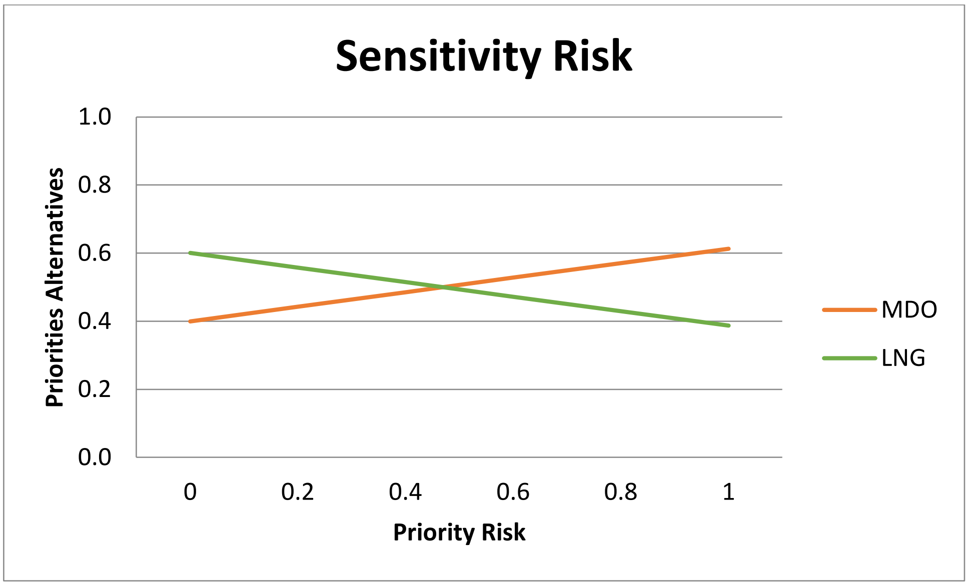

Figure 4.9: Sensitivity Risk

4.7.2 Discussion of the case study results

Our results suggest that compared to MDO, LNG may be the better choice in terms of a vessel investment problem. In the final ranking of alternatives in the case study, we find that LNG is approximately 17% more preferred than MDO. The decision maker weighted several criteria, where *Cost* was the most important, followed by *Technical Performance* and *Risk* being equally important, and lastly *Air Emissions* with the lowest priority. The authors accounted for the expert judgment in rating the alternatives for each criterion, where natural quantitative units such as volume, cost, weight and emission output were used. The exception was the *Risk* criterion, which does not naturally provide a quantitative measure. Instead, the rating was obtained using the decision maker's statements on perceived risk for the technologies.

From the study, two tendencies are of special interest. The sensitivity analysis shows that for the *Cost* criterion, the rank difference between LNG and MDO increases linearly as a function of the criterion priority axis. As the *Cost* priority increases, the relative performance of LNG increases compared to MDO in the final rank aggregation. Another observation is that environmental performance appears to be more important to the decision process, than what the decision maker may think. Even though the decision maker ranked the Air Emissions criterion last in terms of priority, it still contributed to the overall score for the alternatives. If the Air Emissions criterion was given a higher priority, a possible outcome would be a higher discrepancy in the final ranking of the alternatives in favor for the LNG alternative.

These final ranking of the alternatives is in this study not as important in itself. After all, the case study conducted is based on a decision that has already been made. However, mapping the decision process for a decision maker in terms of vessel investment gives us a better insight to areas of importance to the decision maker. The results obtained from this study supports the claims made in chapter 1 and 3, that MCDA can help structure complex decision problems. As evident from the results, an analysis of the weights and ranking gives insight to the decision process, and makes elusive aspects of the process more tangible. A sensitivity analysis gives valuable insight into the relative power of the individual criterion, and how they modulate the final rank aggregation.

The results also suggest that environmental performance (Air Emissions) is an important criterion, even though it was given the lowest weight of the four compound criteria at 18.5%. Between MDO and LNG, the latter alternative rated decidedly better for all three Air Emission sub-criteria (NO_x, SO_x and CO_2). If Air Emission had obtained a higher weighting, the relative ranking of LNG and MDO would change even more in favor for LNG.

Several studies have used MCDA and AHP, also in combination with investment, ships and transport studies. The application of AHP in a ship investment problem for short sea cargo vessels have, to the knowledge of the authors, not yet been done. The inclusion of environmental criteria are widely used. Turcksin et al. used a AHP-PROMETHEE approach to identify and select policy measures to stimulate a clean vehicle fleet (2011). This study takes a somewhat similar approach, utilizing AHP to facilitate the selection of a short sea cargo vessel, with an emphasis on environmental criteria in the context of stricter regulations in Emission Control Areas. A novel feature of this thesis is the use of systems engineering in combination with MCDA in setting up the decision context structure.

In this study, we also conducted a brief environmental screening of the air emission performance (see 4.4.1). For the NO_x and SO_x categories, our results were within 10% of the average emission data reported for the categories. On CO_2 emissions for the alternatives, our calculations were somewhat more conservative than what is reported by the industry (Rolls-Royce Marine, 2012; DNV, 2010), but in line with the numbers suggested by the IMO (CNSS, N.D.; Buhaug et al., 2009).

The results of the vessel selection problem are very much localized. These results reflect the views and propensities of the decision maker, and the expert judgment by the authors in the ratings model. Weightings and expert judgments may be subject to bias, including under- and over estimation and a limits to how many considerations that can be considered simultaneously without losing oversight (Bulut et al., 2012; Kahneman and Tversky, 2000). Bulut et al. revealed that in the existing literature, many scholars presented (fuzzy) AHP models without discussing inconsistencies in the decision matrices (2012). In this case study, this is however discussed, and could may be a limitation of the study. In the case study, the decision maker exhibited a high inconsistency in the initial weightings, which warranted a re-ranking through direct assessment, which again gave zero inconsistency. The case study was also narrowed to one decision maker. A broader context should include the customer as well as the shipyard. The ship owner stressed that the reason why LNG was considered in the first place was the propensity of the customer to accept higher costs for better environmental performance. In retrospect, it could be interesting to compare these aspects – especially to formalize the cost/environment trade-off in a model.

In further research, a scenario-based approach on fuel policy could be employed (see Turcksin et al., 2011). Scenarios should here be decisions accounting for future regulations on emissions, as well as fuel security and cost. A more thorough model should be made for the environmental performance of alternatives, possibly taking into account the total life cycle emissions and cost (LCA and LCC).

The case study, methods and technologies will be summarized and discussed in chapter 5 below.

5 Summary and discussion

In this discussion, the general themes explored in the thesis will be briefly summarized and discussed.

5.1 MCDA in the maritime sector

MCDA methods and AHP in particular[1] have not seen extensive use in maritime decision-making. From literature and applications in other fields, it is evident that proper structuring of problems and decisions helps to identify relevant criteria and alternatives, and helps to minimize redundancy. Decision-making typically consists of identifying alternatives and evaluating trade-offs. A MCDA helps to structure the evaluations to encompass several, often competing aspects in order to identify and rank the most preferred solution in a certain decision context. The primary aim of this study is to demonstrate the application of MCDA through AHP in a vessel selection problem.

A feature of this case study is that environmental considerations are made more explicit, in that they are given a formal presentation as a criterion in a vessel investment case. If asked, most decision makers would almost certainly say they account for environmental performance. Either to meet regulations and pressure, lower cost, or in many cases both. That is however not to say that environmental aspects are integrated into the decision context in the same way for instance cost and performance is measured and analyzed.

An outcome of the case study is the realization that environment in fact needs to be treated with the same scrutiny by decision makers – especially with the increasing regulations on maritime emissions. In this case study, the decision maker had some measure of importance attached to environmental performance. However, once a decision system was structured and the decision maker’s preferences were formalized, the decision maker could ascertain better by how much or less environmental performance was valued compared to the other criteria. As it turned out, from the initial weighting, environment was given a higher preference in some comparisons. A re-ranking revealed that the decision maker in fact ranked environmental last – although not by much.

Ascertaining a complete overview of the limitations, constrains and possibilities pertaining to investments can possibly increase the precision in which decisions are made. Like snowflakes, every decision scenario is different. However, by looking at historical trends and collecting

[1] It has later come to the attention to the authors that one shipyard in Norway utilize AHP in a vessel optimization context.

documentation on decisions, we can obtain a better insight into maritime decision-making and find relevant similarities and tendencies.

5.1.1 Application of AHP in vessel investment

AHP considers both objective and subjective information and helps the decision maker to understand and structure the problem. This is an advantage in order to obtain a more complete process for eliciting the preferences of the decision maker. One reason to use AHP in a vessel investment case is that it is an intuitive, neutral and transparent method. AHP is easy to use and to understand for the decision maker. Although the case study is performed for a specific vessel selection, the approach can be adopted as a model and used in similar cases.

In this study, a great focus has therefore been placed on transparency, as it is the intention that AHP is a transparent method. The systems engineering approach to MCDA, developed in this study, supports this concept. When applied in the case study, it provided a systematic guide, which applies not only to this particular study, but can be used in any AHP decision context. This approach is explained in detail in chapter 3.6, and applied to the case study in chapter 4.5. When presented as a step-wise overview, the information of how the study was conducted is readily available to the reader. In literature where AHP has been used, some steps are often presented – however usually not in a systematic fashion, and often, only brief or no elaborations on the choice for criteria have been provided. A thorough presentation of criteria and alternatives are presented throughout chapter 4. A brief discussion on criteria, alternatives, ratings and inconsistencies are discussed below.

5.1.1.1 Criteria

In this thesis, four main criteria have been identified and selected (Air emissions, Cost, Technical properties and Risk). In this case study, and within this specific decision context, we believe the chosen criteria (and sub-criteria) are sufficient in ensuring that significant aspects and objectives are met, and that unnecessary factors are disregarded. The criteria are assessed in Table 5.1, using the list of considerations presented in chapter 3.4.2.

Table 5.1: Criteria assessment.

Value relevance	All the criteria holds value to the decision maker. Where it is assumed that the decision maker will be indifferent, like with discriminating between NO_X, SO_X and CO_2, the criteria value have been aggregated. That is to say – while these are important to the decision maker (because of regulations, environmental concerns etc.) as a category, they may not be individually important to the decision maker.
Understandability	The same applies here as what is described under "value relevance". See also chapter 4.6.1 for an example of a misapprehension of the ranking method, and how this was solved.
Measurability	All criteria have been given natural quantitative units, such as weight, cost and speed. The exception here is the risk criterion, which is expressed in perceived risk of changing technology, with a verbal scale.
Redundancy	Redundancy have been avoided by making sure the criteria are not measuring the same factor.
Completeness	In this study, some consideration has been taken to keep the model complete. Therefore, criteria such as CAPEX and OPEX are presented as aggregations of several sub-criteria. In this way, the level of detail is kept at a required minimum, while capturing the key aspects of the problem – without risking cluttering the model with too many or redundant criteria.
Operationality	The model in this study has been structured in such a way that it is operational.
Mutual independence of preferences	The criteria are preferential independent.
Size (simple/complex)	As mentioned under "redundancy" and "completeness" above. See also chapter 4.5.3.

However, if the decision context and project scope were to include additional decision makers, such as the customer and shipyard, the list of criteria would have to reflect their concerns and objectives as well. As it turns out, selecting the perfect range of criteria while still encompassing and considering all aspects and relevant features is difficult – if not impossible. Like in decision problems in general, there are always trade-offs and limitations. In this case study, we chose to set the threshold for discriminating between criteria somewhat high. For instance, disaggregating criteria like OPEX into several sub-criteria would greatly increase the number of pairwise comparisons needed from the decision maker. Further disaggregation was avoided to promote only the most relevant criteria, and to prevent high inconsistencies. Too many comparisons and the decision maker may lose oversight. If it seems necessary to disaggregate into many sub-criteria (like disaggregating OPEX into its constituents), a test model may be developed. In this way, a sensitivity screening could be performed to ascertain the relative importance of these sub-criteria.

5.1.1.2 Alternatives

The alternatives have been thoroughly described in chapter 4.3. According to value-theory (Keeney, 1994), alternatives may be derived from the process of identifying criteria. In this case study however, the alternatives were already present. In such, this process has not been followed. Therefore, a short value assessment may be necessary.

We can assess whether or not the chosen alternatives are selected to best achieve the value of the decision maker and the decision problem. In this case study, Ulvan Rederi AS are in the process of launching two new LNG vessels commissioned by Marine Harvest, with the hull constructed at Fiskerstrand Verft (shipyard) and design work from Multi Maritime. Since these alternatives were already "fixed" in the setting of our case study, we must broaden the scope to allow for the customer and shipyard, and possibly the ship design consultancy, to ascertain the value pertained to the alternatives by the decision makers.

According to the ship owner, Marine Harvest attributed a great emphasis on environmental performance. Fiskerstrand Verft stays competitive in the market with efforts in R&D, conceptual developments of new vessel types and by emphasizing collaboration between customers, producers and academia (Fiskerstrand Verft, 2014). For the ship owner, technical performance is important. Low fuel consumption (high fuel efficiency) means lower fuel prices, and happens to increase the environmental performance of the vessel at the same time. According to the ship owner, hull design and materials (for instance hull coating) also improves the efficiency of the vessel. The LNG alternative in this study is the first of its kind, and from the specifications given, it conforms well to these values. The MDO alternative represents "business as usual". While diesel driven engines are the norm, there is still room for innovation within the technology. Therefore, the selection problem becomes a question of improving the options already present, or to invest in new technology. The decision is thus not "which LNG vessel to invest in", but rather "can these values be met by adopting a new technology?". While not clearly stated by the decision maker, present and coming regulations also plays a role in the decision context.

We can thus state with some level of confidence that the criteria, and alternatives, selected for this study conforms to these values. It should be noted that environmental performance and cost are often conflicting criteria. In some instances, like with fuel efficiency, they complement each other – which is where some of the value attained to them lies. Technical performance is another value that is captured in the criteria selection. The risk criterion came to be as a result of the selection of alternatives, as a measure of risk in adopting LNG. This underlines, again, the iterative nature of MCDA, and the lack of linearity in real life applications.

5.1.1.3 Ratings

The use of ratio scales and subsequent normalization allows for the synthesis of the decision maker's priorities. Translating verbal scales into numeric values makes it possible to compare and sum the performance of the alternatives in the decision problem with the decision maker's preferences and priorities. Ascertaining the performance of the alternatives can be done in two ways. Direct rating or the use of pairwise comparison utilizing verbal scales to assess the performance.

There is however a subjective aspect to pairwise comparison rating. Very often, a decision maker will tend to rate alternatives in terms of "Good", "Better", "Worse", "Excellent"; or "High" or "Low"; or maybe "Poor" and "Fair" (Super Decisions, 2013). This can be formalized, by prioritizing the verbal ratings, saying "High" for instance is twice as good as "Medium" and so on. A ratings model like this requires so-called expert judgment in rating the alternatives, and should not be used unless the system contains a well-established evaluation model.

In this study, this verbal rating method have been avoided, by use of direct rating. This has been done to (1) prevent any bias or misunderstandings in terms of how to relate the verbal scale to the performance of the alternatives, and (2) to ensure an objective rating of the performance. Additionally, the decision context is a comparison of fuel technologies in a vessel investment situation, with data based on existing vessels. Therefore, it makes sense for the performance to be measured on a local scale, i.e. a direct assessment of one alternative in relation to the other.

In terms of emissions, all vessels are within a regulated limit. For instance, all vessels built after 2015 will have to adhere to SECA limits. Thus, in rating alternatives a_1 and a_2 on *Air Emissions*, one could construct a scale that reflects an average in Norway, to which the alternatives could be related. However, none of the vessels would of course breach this threshold since emissions are regulated either way. Hence, it makes more sense in this case to compare the two alternatives to each other, because they will either way emit NO_x, SO_x and CO_2 within the legal limit. To further extrapolate this; giving alternative *X* an "Excellent" rating for the *Capacity* criterion and *Y* a "Fair" rating does not really give any sense of how they really relate to each other – only how they relate to an arbitrary scale. Stating that alternative *X* can carry 40% more than *Y* however, gives a better indication on the actual head-to-head performance of the alternatives.

When constructing a ratings model, importance should be given to how the data is preserved. As shown in chapter 4.6.2, there are some simple calculations performed in order to create ratings. Still, an effort should always be made to preserve nuances, and to make sure that information does not get "lost" when translating data to quantities. This may be especially true for rating alternatives over criteria that are not already natural quantity criteria. When ranking alternatives through pairwise comparisons, these considerations may not necessarily be relevant, because the comparisons are made by a verbal statement of how much one is preferred to the other for an alternative – rather than directly comparing actual quantities to each other for the alternative.

5.1.1.4 Treating inconsistencies

In pairwise comparison, the decision maker compares criteria (or alternatives) to one another. As the number of comparisons increases, there is a certain risk of inconsistencies. Avoiding inconsistencies completely is therefore difficult, and a limit is on the inconsistency of the judgments of the decision maker is therefore set

Hence, a way to measure these is needed (revisit chapter 3.4.3.3 for a more thorough description). Thus, if the inconsistency coefficient is higher than 10% it would be necessary to review and to clarify the stakeholder preferences. For this reason, it is important to take care in explaining the rating scale used to obtain their preferences, and clarify any information to ensure the correct answering process of the survey. There are however always room for error, and in chapter 4.6, we show that the first weighting of the compounded criteria received an overly high inconsistency score. This however was immediately noticed and the decision maker was prompted to perform a more direct ranking of the compounded criteria, so that a better ranking could be established.

It should be noted that while AHP is a popular MCDA method, it has also garnered some critique. Rank reversal is a commonly criticized situation that can occur when adding or deleting criteria or alternatives. What has to be understood of rank reversal is that it is natural in the decision-making process. When a new alternative is included in the decision problem, the weights and the scores relative to each of the alternatives will change. This stresses the importance of recalculating weights and to adapt the problem to the new decision context, including a new alternative (Steele et al., 2009). Consequently, the weights and scores should be aligned.

5.1.1.5 Lessons from systems engineering

Quality of decision-making, and at which stage the decisions are taken can determine the success of a project. Theories of systems engineering (SE) demonstrates that the need for proper decision support is key. In a life cycle cost (LCC) perspective, 80% of the costs are determined when 20% of costs have been accrued. I.e., costs are determined early in the planning, thus progressing non-linearly. Hasty decisions amplifies the risk of defects, and like the cost progression, the cost of mistakes multiplies in a non-linear fashion as well (Haskins and Forsberg, 2011).

It may therefore be beneficial to ascertain the close relationship between MCDA and systems thinking, which helped structuring and establishing a proper model for this particular case study. This pilot study contributes to obtain knowledge of the decision-making process in ship investment for ship owners in Norway, to identify important aspects for a ship owner in ship selection and to prove the importance of decision aid tools work for the stakeholder. Some of the decisions are made through the experience of the decision maker, however, when new technologies emerge, as in this case, high levels of uncertainty can be present. For that reason, decision support becomes essential. This type of study can be extended to a policy level to aid the decision-making process for the implementation of new policies in the maritime sector.

5.2 Short sea shipping of cargo – viability of LNG in meeting environmental regulations

Cargo transportation has a detrimental effect on the environment, and more so from road transportation than from short sea shipping. Despite the latter being more energy efficient and less polluting than the alternative, an increasing amount of cargo in Norway is being transported by road than by sea. In this thesis, we have looked at some of the possibilities and constraints in driving the distribution from road hauling back to short sea shipping.

A major constraint that the industry is facing, are tougher requirements on the environmental performance of the technologies, mainly from the quality and type of fuels utilized. In the coming years, increasing pressure on greenhouse gas reduction will enforce stricter regulations on air emissions from the industry (Bengtsson et al., 2014). Other challenges to Norwegian competitiveness in the maritime sector are high production costs and increasing global competition. We argue that due to strict regulations, environmental performance is one such competitive restraint. Consequently, in tackling these challenges, the maritime sector needs to adopt a sustainable approach; cleaner technology, leaner production and overall higher efficiency of materials, cost and energy. A possible step to achieve this are better technology alternatives.

Emissions of NO_x, SO_x and CO_2, and the pertaining regulations, are the main limitations for adopting new technologies. There are many marine propulsion technologies currently available, or attainable in the near future. Most of these are however either not mature enough as technologies; such as biodiesel, solar power and hydrogen fuel cells, or unrealistic for short sea ships; nuclear power and wind (turbine) generation. Thus, the most attainable strategy seems to be to reduce emissions and meet regulations is to focus on fuel technologies.

This can be achieved in two ways. Changing the fuel to a similar type that comply with regulations, or changing the fuel technology. According to recent literature, the most straightforward options are first; adopting a diesel fuel with a sulfur content of <0.1%, in combination with exhaust abatement measures to fulfill with NO_x ECA limitations, or second; making the switch to LNG (Bengtsson et al., 2014; Brynolf et al., 2013; Bengtsson et al., 2012). The latter, which is the focus of this thesis, does not require abatement measures. Compared to conventional marine fuels, LNG reduces sulfur emissions by nearly 100%, in addition to significant reductions of $NO_{x,}$ and finally, considerable reduction of CO_2.

There is thus an initiative in Norway to promote LNG as a future fuel technology for short sea shipping. Thus, the Norwegian government is investing in LNG as a technology in meeting present and future regulations. Although it is considered a new technology, compared to conventional fuels, it is still highly available compared to another new, sustainable alternative, namely biodiesel. Like LNG, biodiesel is essentially free of sulfur. While biodiesel energy is also released through the combustion of hydrocarbons, it is not from a fossil origin. Rather, biofuels can be derived through various plant crops or other organic materials such as production waste from food or other industries. However, as pointed out by Opdal and Fjell Hoyem, neither the engine technology or the infrastructure for biodiesel is mature in its current practice (2007). Other alternatives that can fit with regulations are nuclear propulsion, hydrogen fuel cell and electric wind powered propulsion systems. As with biodiesel, neither of these can be implemented as readily as with LNG.

While LNG may be more mature as a technology and as a market commodity, some big issues needs to be addressed before LNG can be utilized in the scale envisioned by the political and regulative bodies. Norway is arguably the country with the best prospects to meet the future expected demands for LNG. There are already 45 vessels operating on LNG in Norway as of 1013, fueled by 33 terminals. Norwegian company Gasnor already provides bunkering for 22 ships, with 1500 operations a year (Haram, 2014). There are already two LNG tankers and 30 trailers distributing LNG. That means that Norway currently has the best LNG coverage – but this capacity will soon be surpassed by the increasing demand.

The consensus is that to meet the challenges, LNG-infrastructure and price must come to a more acceptable level (Forskningsrådet, 2012; Nørgaard, 2013; Haram, 2014; NHO, 2013). For industries using natural gas as the main source of energy or raw material, price is the most important factor. The natural gas price in Norway is among the highest in the world, and the infrastructure capacity makes gas less available as an option (Forskningsrådet, 2012). In the case study, the use of LNG was very much determined by the customer's interest in the technology to maintain a green image, and its will to provide and set up the infrastructure necessary. This may also be attributed to the steady nature of fish feed transportation, in the sense of the regularity of the cargo and customers. In another case, even with the will to pay more for the technology, the infrastructure may act as a bottleneck.

Finally, the implementation of risk is not limited by the capacity of distribution alone. The cost level, climate regulations and political risk also needs to be addressed (Forskningsrådet, 2012). The potential for this technology is thus great, but the political and regulative bodies needs to improve the business environment and react quicker to the rapid changes brought forth in the market (Forskningsrådet, 2012; NHO, 2013).

5.2.1 What are the implications for the Norwegian maritime sector?

While the Norwegian maritime sector is well known for its maritime competence, there are however other maritime clusters such as Japan, South Korea and China with a much larger presence on the global market. Consequently, the Norwegian maritime industry needs to be more competitive and proficient. Low prices of shipbuilding in other maritime clusters make them more attractive, which requires Norwegian businesses to emphasize innovation and quality of performance in order to stay competitive.

Competitiveness in other aspects than low costs requires new types of decisions to be made on considerations such as environmental performance, technical design, social objectives, new technologies and compliance with policies. New and better decision support tools must therefore be adopted, and they must reflect competitiveness as a value shared by ship owners, shipyards and customers. The principal goal of this study has been to contribute to this development, and the chief output of this thesis has been the implementation of a decision support model, and development of an approach used on a case study for a Norwegian ship owning company.

6 Conclusion

Some of the main challenges to Norwegian competitiveness in the maritime sector are high production costs, increasing global competition and environmental regulations. In tackling these challenges, the maritime sector needs to adopt a sustainable approach; cleaner technology, leaner production and overall higher efficiency of materials, cost and energy. A possible step to achieve this are better technology alternatives. In this thesis, we argue that in order to make this shift happen, better decision support tools must be implemented. The primary goal of this study has been to contribute to the development of DSTs for the maritime sector, and test one such model on a case study for the ship owning company Ulvan Rederi AS.

In contributing to the development of DSTs to the maritime sector, multi-criteria decision analysis (MCDA), specifically the Analytic Hierarchy Process (AHP), has been used to facilitate the selection of new vessels at the case company. Several criteria were selected to represent the main considerations related to the problem. The ship owner’s preferences were elicited in order to weigh these criteria to ascertain their importance in the selection problem. The result of the case study shows that in a vessel selection decision, a vessel powered by LNG was preferred over a vessel utilizing conventional marine diesel. This result, however, depends somewhat on the decision context. A sensitivity analysis shows that when some criteria are more or less preferred, the final ranking of the alternatives will change. In this study, it was concluded that changes in preferences did not cause a rank reversal of the alternatives. An important feature of the model in this study is the inclusion of criteria representing environmental performance. The most important criteria identified in the case study were air emissions, cost, technical performance and risk.

While short sea cargo transportation pollutes less than road transportation per tonne-kilometre, stricter regulations on NO_x, SO_x and CO_2 in the coming years necessitates a stronger emphasis on environmental performance. This study shows that the ranking of the alternatives will differ drastically in favor of LNG if the criteria representing environmental performance is more preferred. In the study, the ship owner ranked the environmental performance category last, but recognized the importance of including environment as a criterion. In the future, the ship owner reckoned environmental performance would have a much higher priority. In conclusion, the results indicate the absolute importance of including environment as a parameter in maritime decision-making, and may be especially important in areas subject to sulfur and NO_x restrictions. It also confirms that MCDA, and AHP, can be used to aid decision makers in structuring their priorities in a decision-making context.

An additional outcome of the study was the development of a systematic representation of MCDA through systems engineering principles. This mode of approach helps to simplify and structure the decision context of a MCDA, and understanding the systematic nature of decision problems.

6.1 Limitations and further research

Some limitations of the study were identified. In the case study, only one decision maker was selected. A more encompassing study could possibly include the shipyard and customer as additional decision makers. In identifying more decision makers, a stakeholder analysis could be included. This would strengthen the study by enabling the researchers to discriminate between the values of different decision makers, which would help to capture the complexity of the decision context and problem.

The results from this study shows that environmental concerns has a relevance in vessel investment, and when formalized as a criterion in a MCDA has a considerable impact in the decision process. In this study, only the most relevant emissions to air were selected. Further research may improve the obtained results through the inclusion of more environmental criteria. An actual comparison of the environmental performance of the technologies through a life cycle assessment (LCA) could be advantageous in formulating a better foundation for the rating of alternatives in relation to the environmental criteria. This would require the consideration of emissions to soil and water, and other areas of impact. In the context of maritime regulations, the new Energy Efficiency Design Index could be included as a technical and operational measure of environmental performance.

Finally, a formal analysis on the relationship between MCDA and systems engineering may be beneficial to further improve MCDA as a discipline.

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Appendix A Questionnaire for pairwise comparisons

NTNU – Trondheim
Norwegian University of
Science and Technology

MULTI-CRITERIA DECISION ANALYSIS IN THE NORWEGIAN MARITIME SECTOR
Selection of vessel alternatives

You are deciding on a new vessel investment. Which of the following criteria do you find most important in this setting?

For every step, select the most important criterion and use the provided scale to determine its importance in comparison to the other.

1 Select the most important criterion between ***Environmental Performance*** and ***Costs***

☐ Environmental Performance ☐ Costs

On a scale of 1-9, how much more important do you find the chosen criterion?

Equally important		Slightly more important		Strongly more important		Very strongly more important		Extremely more important
1	2	3	4	5	6	7	8	9

2 Select the most important criterion between ***Environmental Performance*** and ***Risk***

☐ Environmental Performance ☐ Risk

On a scale of 1-9, how much more important do you find the chosen criterion?

Equally important		Slightly more important		Strongly more important		Very strongly more important		Extremely more important
1	2	3	4	5	6	7	8	9

3 Select the most important criterion between ***Environmental Performance*** and ***Technical Performance***

☐ Environmental Performance ☐ Technical Performance

On a scale of 1-9, how much more important do you find the chosen criterion?

Equally important		Slightly more important		Strongly more important		Very strongly more important		Extremely more important
1	2	3	4	5	6	7	8	9

4 Select the most important criterion between ***Costs*** and ***Risk***

☐ Costs ☐ Risks

On a scale of 1-9, how much more important do you find the chosen criterion?

Equally important		Slightly more important		Strongly more important		Very strongly more important		Extremely more important
1	2	3	4	5	6	7	8	9

5 Select the most important criterion between ***Costs*** and ***Technical Performance***

☐ Cost ☐ Technical Performance

On a scale of 1-9, how much more important do you find the chosen criterion?

Equally important		Slightly more important		Strongly more important		Very strongly more important		Extremely more important
1	2	3	4	5	6	7	8	9

6 Select the most important criterion between ***Risk*** and ***Technical Performance***

☐ Risk ☐ Technical Performance

On a scale of 1-9, how much more important do you find the chosen criterion?

Equally important		Slightly more important		Strongly more important		Very strongly more important		Extremely more important
1	2	3	4	5	6	7	8	9

7 Select the most important criterion between ***CAPEX*** and ***OPEX***

☐ CAPEX ☐ OPEX

On a scale of 1-9, how much more important do you find the chosen criterion?

Equally important		Slightly more important		Strongly more important		Very strongly more important		Extremely more important
1	2	3	4	5	6	7	8	9

8 Select the most important criterion between ***Speed*** and ***Cargo Capacity***

☐ Speed ☐ Cargo Capacity

On a scale of 1-9, how much more important do you find the chosen criterion?

Equally important		Slightly more important		Strongly more important		Very strongly more important		Extremely more important
1	2	3	4	5	6	7	8	9

Appendix B EIAPP Certificate, With Junior

KINGDOM OF BELGIUM

FEDERAL PUBLIC SERVICE
MOBILITY AND TRANSPORT

MARITIME TRANSPORT

ENGINE INTERNATIONAL AIR POLLUTION PREVENTION CERTIFICATE

Issued under the provisions of the Protocol of 1997, as amended by resolution MEPC.176(58) in 2008, to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 related thereto (hereinafter referred to as "the Convention") under the authority of the Government of :

……………………………………………….BELGIUM…………………………………………………
(full designation of the country)

by Federal Public Service Mobility and Transport…………………………………………………
(full designation of the competent person or organisation authorized under the provisions of the Convention)

Engine Manufacture	Model Number	Serial number	Test Cycle(s)	Rated power (kW) and speed (rpm)	Engine approval number
Anglo Belgian Corporation	8 DZC	13613	E3	1840kW at 1000rpm	NOx-2010-0005

THIS IS TO CERTIFY:

1. That the above-mentioned marine diesel engine has been surveyed for pre-certification in accordance with the requirements of the Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines 2008 made mandatory by Annex VI of the Convention; and

2. That the pre-certification survey shows that the engine, its components, adjustable features, and technical file, prior to the engine's installation and /or service on board a ship, fully comply with the applicable regulation 13 of annex VI of the Convention.

This Certificate is valid for the life of the engine, subject to surveys in accordance with regulation 5 of Annex VI of the Convention, installed in ships under the authority of this Government.

Issued at **Brussels**
(Place of issue of certificate)

20 September 2011
(Date of issue)

………………………………………………
(signature of duly authorized official issuing the certificate)

Ir. Jos HEYNDERICKX
Adviseur-generaal

(Seal or stamp of the authority, as appropriate)

Federale Overheidsdienst Mobiliteit en Vervoer
Maritiem Vervoer

2 Particulars of technical file

The technical file, as required by chapter 2 of the NO_x Technical Code 2008, is an essential part of the EIAPP Certificate and must always accompany an engine throughout its life and always be available on board a ship.

2.1 Technical file identification/approval number: NOX-2010-0005-TF0242011

2.2 Technical file approval date: 19 September 2011

3 Specifications for the onboard NO_x verification procedures

The specifications for the onboard NO_x verification procedures, as required by chapter 6 of the NO_x Technical Code 2008, are an essential part of the EIAPP Certificate and must always accompany an engine through its life and always be available on board a ship.

3.1 Engine parameter check method:

3.1.1 Identification/approval number: NOX-2010-0005-MV0242011

3.2 Approval date: 19 September 2011

3.3 Direct measurement and monitoring method: not applicable

3.3.1 Identification/approval number: not applicable

3.2.2 Approval date: not applicable

Alternatively the simplified measurement method in accordance with 6.3 of the NO_x Technical Code 2008 may be utilized.

Issued at **Brussels**

(Place of issue of certificate)

20 September 2011
(Date of issue)

(Signature of duly authorized official issuing the certificate)

(Seal or stamp of the authority, as appropriate)

Ir. Jos HEYNDERICKX
Adviseur-generaal

Federale Overheidsdienst Mobiliteit en Vervoer - Maritiem Vervoer

2/2

SUPPLEMENT TO ENGINE INTERNATIONAL AIR POLLUTION PREVENTION CERTIFICATE (EIAPP CERTIFICATE)

RECORD OF CONSTRUCTION, TECHNICAL FILE AND MEANS OF VERIFICATION

Notes:

1 This Record and its attachments shall be permanently attached to the EIAPP Certificate. The EIAPP Certificate shall accompany the engine throughout its life and shall be available on board the ship at all times.

2 The Record shall be at least in English, French or Spanish. If an official language of the issuing country is also used, this shall prevail in case of a dispute or discrepancy.

3 Unless otherwise stated, regulations mentioned in this Record refer to regulations of Annex VI of the Convention and the requirements for an engine's technical file and means of verifications refer to mandatory requirements from the revised NO_x Technical Code 2008.

1 **Particulars of the engine**

1.1 Name and address of manufacturer: Anglo Belgian Corporation nv. Wiedauwkaai 43, 9000 Gent(Belgium)

1.2 Place of engine build: see 1.1

1.3 Date of engine build: 02 August 2011

1.4 Place of pre-certification survey: see 1.1.

1.5 Date of pre-certification survey: 02 August 2011

1.6 Engine type and model number: 8 DZC-1000-173-A

1.7 Engine serial number: 13613

1.8 If applicable, the engine is a parent engine ☐ or a member engine ☒ of the following engine family ☐ or engine group ☒ : DZ group (830-1000)

1.9 Individual engine or engine family / engine group details:

1.9.1 Approval reference: NOx-2010-0005

1.9.2 Rated power (kW) and rated speed (rpm) values or ranges: 1840kWx1000rpm

1.9.3 Test cycle(s):E3

1.9.4 Parent engine(s) test fuel oil specification: not applicable

1.9.5 Applicable NO_x emission limit (g/kWh), regulation 13.4: 8.98 g/kWh

1.9.6 Parent engine(s) emission value (g/kWh): E3=7.6g/kWh

Appendix C Datasheet for ABC Diesel Engine type DZC

ANGLO BELGIAN CORPORATION, N.V.

Wiedauwkaai, 43
9000 Gent - BELGIUM
Tel.: ++ 32 9 267 00 00
Fax: ++ 32 9 267 00 67
e-mail: info@abcdiesel.be

Datasheet for ABC Diesel Engine type DZC

Operational circumstances based on ISO–conditions (ISO 3046-I).

ABC reserves the right to alter the technical data without prior notice.

DEFINITION

DZC: Medium speed engine, turbocharged & intercooled, available in Anti-clock and Clock rotation.

BASIC DATA

Cycle: 4 stroke, single acting.
Cylinders: 6-8 in line.
Bore: 256 mm.
Stroke: 310 mm.
Swept volume: 6 cylinders: 95.7 liters. 8 cylinders: 127.6 liters.
Compression ratio: 12.1: 1
Injection: Direct, mechanical. One pump per cylinder.

PRESSURES

Brake mean effective pressure (bar)

rpm	720	750	800	900	1000
DZC	18.1	17.9	17.3	16.6	16.6

Maximum combustion pressure (bar)

rpm	720	750	800	900	1000
DZC	114	111	109	109	114

Lubricating oil pressure (bar)
(SAE 30 - 75ºC)

rpm	Idle speed		720	900
	300	330	750	1000
6DZC	2 – 2.5	2.5 - 3	4.85	5
8DZC	1.75	2	4.85	5

ROTATION SPEED

Piston speed (m/s)

rpm	720	750	800	900	1000
DZC	7.4	7.7	8.2	9.3	10.3

Fire speed: 120 rpm.

WORKING TEMPERATURES (ºC)

	Normal	Alarm	Stop
HT-cooling	80-85	90	95
Luboil (LT)	71-75	80	85
Luboil (HT)	76-81	85	90

MASS MOMENT OF INERTIA

6DZC including flywheel: 145 kgm^2
8DZC including flywheel: 181 kgm^2
Data based on standard version.

FUEL CONSUMPTION

g/kWh (g/HPh)

rpm	720	750	800	900	1000
6DZC	189 (139)	186 (137)	187 (138)	189 (139)	190 (140)
8DZC	188 (139)	188 (139)	188 (139)	191 (141)	193 (142)

For fuel oil:
- *net heat value of 42700 kJ/kg,*
- *without engine-driven pumps,*
- *tolerance: + 5%.*

OIL CONSUMPTION

6-8DZC: 0.7 g/kWh (0.5 g/HPh)

HEAT REMOVAL

(kW_{th} / kW_{eng})

Jacket cooling water:
6DZC: 0.28 **8DZC:** 0.305

Charge air cooling water:

rpm	cyl	120	135	150	166	179
720	6	---	---	---	0.248	0.253
	8	---	---	---	0.237	0.252
750	6	---	0.234	0.242	0.248	0.253
	8	---	---	0.216	0.237	0.250
900	6	0.158	0.177	0.194	0.213	---
	8	---	0.161	0.176	0.190	---
1000	6	0.189	0.212	0.237	0.262	---
	8	---	0.208	0.232	0.240	---

Lubricating oil:

rpm	cyl	120	135	150	166	179
720	6	---	---	---	0.098	0.092
	8	---	---	---	0.095	0.090
750	6	---	0.115	0.106	0.098	0.092
	8	---	---	0.100	0.095	0.092
900	6	0.129	0.122	0.114	0.106	---
	8	---	0.122	0.114	0.106	---
1000	6	0.121	0.114	0.106	0.099	---
	8	---	0.118	0.110	0.104	---

FLOW OF FLUIDS

High Temperature circuit: (m^3/h)

rpm	720	750	800	900	1000
6DZC	36	39	43	48	54
8DZC	52	54	57	64	72

Low Temperature circuit: (m^3/h)

rpm	720	750	800	900	1000
6-8DZC	43	45	48	54	60

Lubricating oil: (m^3/h)
(SAE 30 - 75ºC)

rpm	720	750	800	900	1000
Pump capacity	31	32	33.8	38	42
6DZC	19.3	19.5	19.7	19.8	20.2
8DZC	23	23.5	23.6	23.8	24

AIR & EXHAUST GAS

Inlet air flow: (m^3/s)

rpm	cyl	120	135	150	166	179
720	6	---	---	---	1.74	1.83
	8	---	---	---	2.37	2.52
750	6	---	1.61	1.71	1.82	1.90
	8	---	2.10	2.29	2.48	2.62
900	6	1.64	1.79	1.95	2.12	---
	8	2.20	2.44	2.66	2.91	---
1000	6	1.97	2.13	2.29	2.47	---
	8	2.62	2.87	3.14	3.42	---

Exhaust gas flow: (m^3/s)

rpm	cyl	120	135	150	166	179
720	6	---	---	---	3.82	4.08
	8	---	---	---	4.51	4.76
750	6	---	3.40	3.69	4.00	4.26
	8	---	3.95	4.34	4.73	4.98
900	6	3.47	3.83	4.21	4.61	---
	8	4.72	5.20	5.68	6.22	---
1000	6	4.11	4.52	4.94	5.38	---
	8	5.22	5.72	6.20	6.72	---

Exhaust gas temperatures: (ºC)
a = Temperature at cylinder
b = Temperature before turbine
c = Temperature after turbine

6DZC:

rpm	tº	120	135	150	166	179
720	a	---	---	---	390	405
	b	---	---	---	500	520
	c	---	---	---	375	385
750	a	---	365	380	395	405
	b	---	460	485	505	525
	c	---	345	365	380	385
900	a	375	390	400	410	---
	b	475	495	515	530	---
	c	345	360	375	395	---
1000	a	385	400	410	420	---
	b	485	505	525	540	---
	c	355	370	390	410	---

8DZC:

rpm	tº	120	135	150	166	179
720	a	---	---	---	400	410
	b	---	---	---	465	480
	c	---	---	---	345	350
750	a	---	375	385	400	410
	b	---	430	450	465	480
	c	---	325	335	345	350
900	a	375	390	400	410	---
	b	470	490	510	520	---
	c	340	360	380	390	---
1000	a	385	395	410	430	---
	b	470	490	510	525	---
	c	360	375	390	405	---

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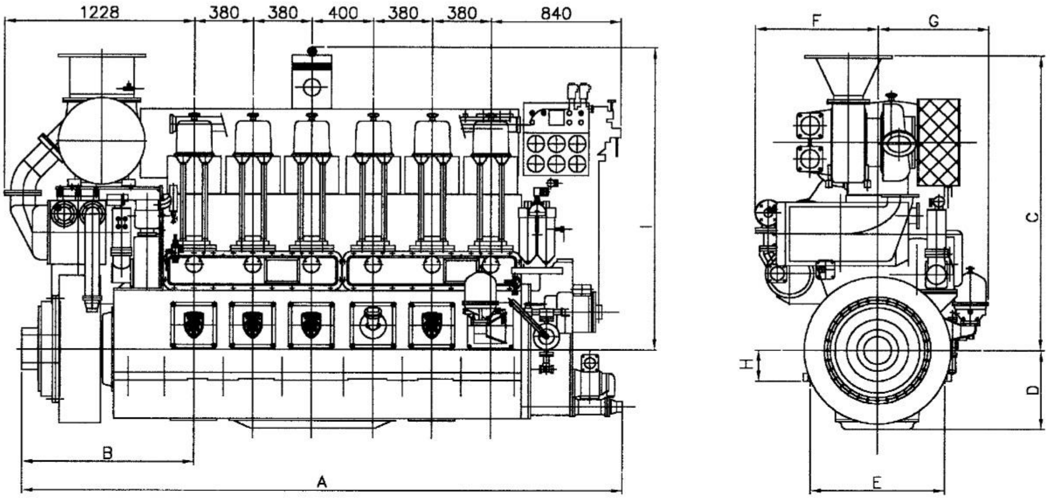
Datasheet for ABC Diesel Engine type DZC

Operational circumstances based on ISO–conditions (ISO 3046-I).

ABC reserves the right to alter the technical data without prior notice.

TYPE OF ENGINE	rpm	POWER OF THE ENGINE (ISO 3046 – I)		NOMINAL POWER OF GENSETS DZC			
				50 Hz electric 3 phase		60 Hz electric 3 phase	
		kW	HP	P_W (kW)	P_n (kVA)	P_W (kW)	P_n (kVA)
6 DZC–720–166	720	954	1297	---	---	907	1134
6 DZC–720–181	720	1032	1403	---	---	975	1218
6 DZC–750–120	750	721	979	685	856	---	---
6 DZC–750–135	750	810	1101	770	962	---	---
6 DZC–750–150	750	900	1224	855	1069	---	---
6 DZC–750–166	750	995	1353	945	1182	---	---
6 DZC–750–179	750	1065	1448	1012	1292	---	---
6 DZC–800–173	800	1104	1500	---	---	---	---
6 DZC–900–120	900	864	1175	---	---	821	1026
6 DZC–900–135	900	972	1322	---	---	923	1154
6 DZC–900–150	900	1080	1468	---	---	1026	1283
6 DZC–900–166	900	1194	1623	---	---	1135	1419
6 DZC–1000–120	1000	960	1305	912	1140	---	---
6 DZC–1000–135	1000	1080	1468	1027	1283	---	---
6 DZC–1000–150	1000	1200	1632	1140	1426	---	---
6 DZC–1000–166	1000	1326	1803	1260	1575	---	---
8 DZC–720–166	720	1272	1729	---	---	1209	1511
8 DZC–720–181	720	1376	1870	---	---	1300	1624
8 DZC–750–120	750	961	1306	913	1141	---	---
8 DZC–750–135	750	1081	1469	1027	1284	---	---
8 DZC–750–150	750	1200	1632	1140	1426	---	---
8 DZC–750–166	750	1326	1803	1260	1575	---	---
8 DZC–750–179	750	1420	1931	1349	1686	---	---
8 DZC–800–173	800	1472	2000	---	---	---	---
8 DZC–900–135	900	1296	1762	---	---	1232	1539
8 DZC–900–150	900	1440	1958	---	---	1369	1711
8 DZC–900–166	900	1592	2165	---	---	1513	1891
8 DZC–1000–135	1000	1440	1958	1369	1711	---	---
8 DZC–1000–150	1000	1600	2176	1521	1901	---	---
8 DZC–1000–166	1000	1768	2404	1680	2100	---	---



TYPE	Mass (kg)*	A (mm)	B (mm)	C (mm)	D (mm)		E (mm)	F (mm)	G (mm)	H (mm)	I (mm)
					Shallow	Deep					
6 DZC	10620	3886	1112	1902	508	650	870	795	715	200	1950
8 DZC	13905	4681	1112	1902	508	650	870	795	715	200	1950

* Flywheel, vibration damper and coolers are included.
Conversion factors used: 1 metric HP = 0.736 kW; Generator efficiency: $\eta G = 0.95$; Power factor: $\cos \varphi = 0.8$

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WITH JUNIOR

Klasse: DNV*1A1 Reefer / Container, Ice C, E0, Nord og Østersjøfart

Bygget: Moen Slip AS, 2009

Hoveddimensjoner:

Lengde over alt	66,70 meter
Lengde mellom pp	61,70 meter
Bredde spant	14,60 meter
Dybde riss	10,82 meter
Dypgående sommer	5,25 meter
Dødvekt	2 040 tonn.
Tonnasje	2 363 BT

Losse- og lasteutstyr:

Dekkskran:

Tungløft, Hovedløft 50 tonn/13,0 meter
Hjelpeløft 12,5 tonn/24 meter

Sideporter:

Hovedport: Arbeidsåpning bredd 7,2 meter
Heiser 2 * 4,1 tonn
Kaivariasjon 1 m ved høyvann
og ca 7,8 m ved lavvann

Luke:

Hydraulisk foldeluke, lysåpning 12,8 x 7,7 meter

Gaffeltrucker:

2 stk 3,0 tonns elektrisk
1 stk 2,5 tonns elektrisk
2 stk 2,0 tonns elektrisk

Maskineri:

Hovedmotorer ABC	1 840 kW
Propell	Diameter 3,2 meter, vribart
Ror	Rolls Roys høy løfte ror
2 stk Sidepr.	Brunvoll, elekt. 450 kW/350kW
Hjelpemotorer Scania	2 stk å 475 ekW/219ekW
Akselgenerator1	700 kW
Service fart last:	12,5 knop.

Lastekapasiteter, Netto:

Lasterom	Areal	Høyde	Volum
Tanktopp	401 m²	2,6 m	1043 m³
Hoveddk, frys	558 m²	1,9 m	1 071 m³
Shelterdk, frys	290 m²	2,55 m	740 m³
Shelterdk,	130 m²	2,65 m	484 m³
Shelterdk, frys	210 m²	2,55 m	535 m³
Totalt frys	**1 058 m²**		**2 346 m³**

Temperaturene kan være uavhengig i de forskjellige fryserommene, minimum –27° C.

Totalt lasterom	**1 593 m²**	**3 873 m³**
Værdekk	**582 m²**	

Container kapasitet.

Under dekk 6 stk 20’ (3 stk frysecont. plugger.)
Vær dekk 29/59 stk 20’(9 stk frysecont. plugger.)

WITH MARINE

**Klasse: DNV *1A1, General Cargo Carrier,
Gas Fuelled, Clean, TMON, E0**

**Bygget: Fiskarstrand Skipsverft,
2014 september**

Hoveddimensjoner:

Lengde o.a.	69,90 meter
Lengde p.p.	68,40 meter
Bredde, mld	17,20 meter
Dybde mld	8,60 meter
Dypgang sommer	≈ 6,50 meter
Dødvekt	≈ 3 300 t
Gross Tonnage	3 250 BT

Dekksutstyr:

2 stk Proviant kraner	1,5 tog 3,0 t
2 stk Fortøyning og Ankervinsjer	
2 stk Fortøyningsvinsjer	
Leveransesystem for Diesel og Ferskvann	
Søppelrom	
Ballast behandlingssystem	100 m^3/t

Bulk lastesystem:

Graintec, lukket system,	300 tonn/t

Bulk lossesystem:

Graintec.,	200 tonn/t
Rekkevidde Bulk kran	27 meter

Bulk Rom

Volum Bulk rom	≈ 5 000 m^3
Antall rom	6 stk
Kapasitet fiskefor	≈ 3 000 t

Maskineri:

Hovedmotor	Rolls Royce C25:33L9P, 2360 kW
Drivstoff	Natural Gas, LNG

Framdrift System

Propell, diameter 3,8 meter, vribart

Generatorer

Aksel generator Var/frekvens	1 900 kW
2 Scania å	570 kW
John Deer	100 kW
Total	3 140 kW

Landstrøm tilkobling under lasting

Manøvrering System:

Sidepropell forut	800 kW
Sidepropell akter	800 kW
DP System, Kongsberg	
Servise fart lastet	13,0 knop

Tank kapasitet.

Natural Gas, LNG	125 m^3
Diesel	70 m^3
Ferskvann	40 m^3