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Selecting technological alternatives for regulatory compliance towards emissions reduction from shipping: an integrated fuzzy multi-criteria decision-making approach under vague environment

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WORLD MARITIME UNIVERSITY
Malmö, Sweden

SELECTING TECHNOLOGICAL ALTERNATIVES FOR REGULATORY COMPLIANCE TOWARDS EMISSIONS REDUCTION FROM SHIPPING

An integrated fuzzy multi-criteria decision-making approach under vague environment

By

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A dissertation proposal submitted to the World Maritime University in partial fulfillment of the requirements for the award of the degree of

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In
MARITIME AFFAIRS

(MARITIME ENERGY MANAGEMENT)

2017

DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

(Signature):

(Date): 19 September 2017

Supervised by:
Dr. Aykut I. Ölçer,

World Maritime University

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ABSTRACT

Title of Dissertation: **Selecting technological alternatives for regulatory compliance towards emissions reduction from shipping: An integrated fuzzy multi-criteria decision-making approach under vague environment**

Degree: **MSc**

Due to the increasing pressure from stricter environmental regulations to reduce emissions in shipping, the maritime industry has been forced to find alternative measures. Nevertheless, it is tough for decision-makers to select the most suitable alternatives for emissions reduction from shipping as it is multi-criteria decision-making (MCDM) problem in which a finite number of alternatives are assessed with respect to multiple criteria as well as different aspects evaluation. Further challenge on such analysis is the lack and/or the inconsistency of information. This study developed an integrated fuzzy MCDM method that combines fuzzy Analytic Hierarchy Process (AHP) and fuzzy Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) for the selection of technological alternatives for regulatory compliance under vague environment. Three spheres of sustainability including economic, environmental and social aspects along with nine criteria were analyzed and evaluated. The weights of aspects and criteria were determined by the fuzzy AHP meanwhile alternatives were prioritized by the fuzzy TOPSIS.

According to the outputs of the proposed decision-making framework, Low-sulphur fuels have been recognized as the most suitable alternative for regulatory compliance, followed by Methanol, Scrubbers and Liquefied natural gas (LNG) correspondingly. Sensitivity analysis was performed to reveal that the proposed framework is quite robust except for the changes of the weight of the criterion Capital cost with another criterion. The proposed method could be an effective decision-making support tool for ship operators to select technological alternatives for regulatory compliance towards emissions reduction from shipping.

KEYWORDS: Shipping, Emissions reduction, Alternatives, Multi-criteria decision-making, Fuzzy AHP, Fuzzy TOPSIS

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
ARB	Air Resources Board
CAPEX	Capital cost
CH_4	Methane
CO_2	Carbon dioxide
E-PRTR	European Pollutant Release and Transfer Register
ECAs	Emission control areas
EEDI	Energy Efficiency Design Index
EFTA4	European Free Trade Association
ELECTRE	Elimination and Choice Translating Reality
EMSA	European Maritime Safety Agency
EU	European Union
FNIS	Fuzzy Negative Ideal Solution
FPIS	Fuzzy Positive Ideal Solution
GHG	Greenhouse Gases
GWP	Global warming potential
HFO	Heavy fuel oil
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
MARPOL 73/78	The International Convention for the Prevention of Pollution from Ships
MCDM	Multi-criteria decision-making
MDO	Marine diesel oil

MEPC	Marine Environment Protection Committee
MGO	Marine gas oil
MRV	Monitoring, Reporting and Verification
N_2O	Nitrous oxide
NH_3	Ammonia
NO	Nitrogen monoxide (NO) and (NO_2)
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
OPEX	Operational cost
PM	Particular Matter
SCR	Selective Catalytic Reduction
SECAs	Sulphur emission control area
SEEMP	Energy Efficiency Management Plan
SO_2	Sulphur dioxide
SO_3	Sulphur trioxide
SO_x	Sulphur oxides
STEAM3	Ship Traffic Emission Assessment Model
TOPSIS	Technique for Order Performance by Similarity to Ideal Solution
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United Nations Framework Convention for Climate Change
VIKOR	Viekriterijumsko Kompromisno Rangiranje
VOCs	Volatile Organic Compounds
WET	Weighted Evaluation Technique

Chapter 1. Introduction

1.1 Background

According to the International Chamber of Shipping, shipping industry is a backbone of global trade, transporting about 90% of the tonnage of all traded commodities. Statistics given by UNCTAD 2016 indicates that world seaborne trade volumes were estimated to surpass 10 billion tons in 2015. This rapid growth of international seaborne trade along with the increase in the number of global vessels gave rise to high energy demand. Over the last 150 years, the energy source for the propulsion of vessels has significantly transformed from sails (renewable energy) to steam (coal) and then the utilization of heavy fuel oil (HFO) and marine diesel oil (MDO), the last two with high emissions becoming the predominant shipping propulsion in the contemporary maritime sector (IRENA, 2015). According to International Maritime Organization (IMO)'s Third GHG Study 2014, for the period from 2007 to 2012, on average, the global shipping fleet consumed between 250 and 325 million tonnes of fuel annually. It has been estimated that world shipping gets blamed for contributing to 870 million tonnes of carbon dioxide (CO_2) emissions, accounting for roughly 3% of annual global anthropogenic CO_2 emissions (Buhaug et al., 2009; Dalsøren et al., 2009; Eide & Endresen, 2011). These emissions intensities from the maritime sector are predicted to rise significantly in the coming decades, tripling from 50% to 250% by 2050 if left unchecked (Smith et al., 2014). In addition, shipping is an important contributor to emitting global anthropogenic sulphur oxides (SO_x) and nitrogen oxides (NO_x) emissions at the figure of 5-10% and 15-30% correspondingly (Corbett & Koehler, 2003; Eyring et al., 2005; Wang et al., 2009).

In favor of addressing the air pollution issue which is attributed to exhaust emissions from ships, the Annex VI of the MARPOL 73/78 Convention which was first adopted in 1997 entered into force in May 2005. Annex VI "sets limits on sulphur oxide and nitrogen oxide emissions from ship exhausts, prohibits deliberate emissions of ozone depleting substances and provides for emission control areas in which more stringent standards apply" (Bellefontaine & Lindén, 2009). The MARPOL 73/78 Annex VI global regulations on the shipping industry mandate the use of bunkers with the sulphur content of a global basis 4.5% then lowered to 3.5% from January 2012. The same regulations entered into force that, the sulphur content limit has to be reduced from 1% to 0.1% after January 2015 in Emission Control Areas (ECAs) namely the Baltic Sea area, North Sea area, North America area (United States and Canada) and United States Caribbean Sea area. It is envisaged that legislation on further SECAs around Australia, Japan, Mexico and in the Mediterranean Sea will be enacted by the IMO in the future (Andersson & Salazar, 2015). It should be taken into account that the Marine Environment Protection Committee's (MEPC) 70th meeting on 27 October 2016 decided that the global fuel sulphur content limit of 0.5% will come into force from January 1, 2020. Table 1 demonstrates the ECAs designated by the IMO with adoption and effective dates whereas table 2 shows the maximum permitted sulphur in fuel oil used by ships operating inside and outside ECAs.

Table 1. Emissions control areas

Emissions control areas	Included emissions	Adopted	In effect from
Baltic Sea	SO_x	26/09/1997	19/05/2006
North Sea	SO_x	22/07/2005	22/11/2007
North America	SO_x, $NO_{x,}$, PM	26/03/2010	01/08/2012
US Caribbean Sea	SO_x, $NO_{x,}$, PM	26/07/2011	01/01/2014

Source: www.imo.org.

Table 2. Limits for sulphur in content in bunker fuels inside and outside ECAs

Outside ECAs	Inside ECAs
4.50% prior to 1 January 2012	1.50% prior to 1 July 2010
3.50% between 1 January 2012 and 2020	1.00% between 1 July 2010 and 1 January 2015
0.5% from 1 January 2020	0.1% from 1 January 2015

Source: www.imo.org

Tier III NO_x emissions legislation, as shown in figure 1, has also been enforced in specified ECAs designated by the IMO, affecting all new vessels built after 2016. This legislation has been effective in North America and United States Caribbean Sea area from 2016 onwards and is expected to be implemented in the Baltic Sea area (Andersson & Salazar, 2015).

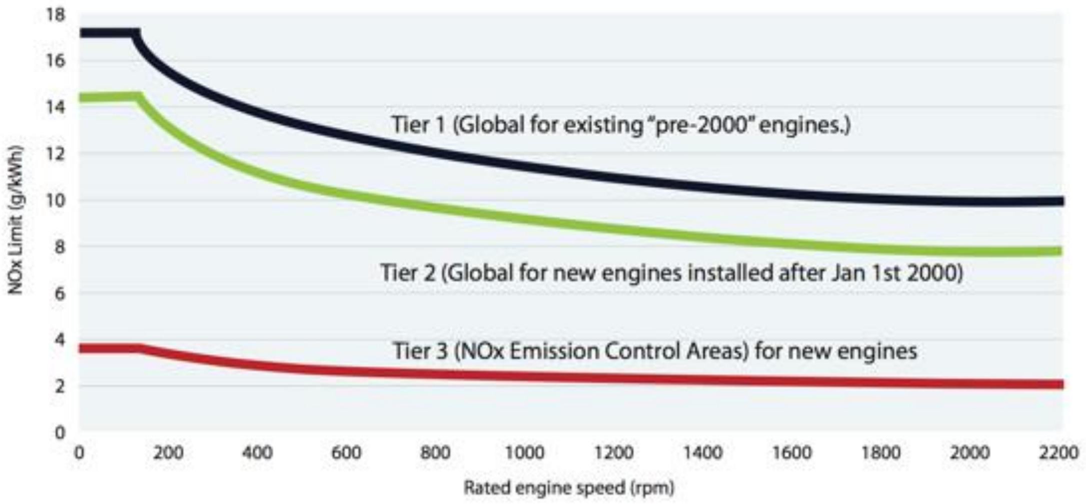


Figure 1. NOx emissions regulations for new-build ships in ECAs

Source: www.imo.org

Green House Gases (GHG) emissions from maritime industry are not included in the Kyoto protocol. The development of the mechanism required to limit the GHG emissions has been assigned to the IMO. Particulates emissions that have harmful effect on human health have not been controlled yet, but are expected to decline aligned with reducing sulphur content. A particular type of particulate is black carbon, which might exert climate effect. Particulate are normally measured by number as well as by mass. However, a massive number of small particles pose a serious health hazard to humans (Andersson & Salazar, 2015).

A thorny problem perplexing shipowners and operators is the compliance with existing and upcoming regulations. There are a variety of possible options should be considered to meet these requirements. One of the options is running on heavy fuel oil (HFO) (3.5% S) along with the installation of exhaust gas cleaning systems (referred to as maritime scrubbers). The second alternative would be to switch to fuels with lower sulphur content (referred to as compliant fuels or distillates). Installing new machinery or retrofitting of existing machinery where possible to utilize Liquefied Natural Gas (LNG) has also attracted the interests of maritime operators. Switching to Methanol is also a good potential alternative for reducing emissions from shipping (ABS, 2017; Dalaklis et al., 2016; IMO, 2016; Ellis & Tanneberger, 2015). Nevertheless, decision-makers (shipowners and operators) find the selection of technological alternatives for regulatory and environmental compliance challenging because it is a multi-criteria decision-making (MCDM) issue which relates to prioritizing or ranking a finite number of alternatives with respect to multiple criteria evaluation. Furthermore, they are also faced with a problem of incomplete and vague information in the criteria evaluation with different dimensions such as economic, environmental and social aspects.

In recent years, MCDM method is a powerful tool applied broadly to address technological alternatives selection problems containing multiple conflicting criteria. One of MCDM method is fuzzy TOPSIS (Technique for Order Performance by Similarity to Ideal Solution) which has been recently used for dealing with the uncertainties and deficiencies. The literature has experienced the difficulty in determining the weights of the criteria and keeping consistency of judgment when employing fuzzy TOPSIS. Hence, the integration of the fuzzy TOPSIS with another technique, such as fuzzy AHP (Analytic Hierarchy Process), have the possibility of obtaining the criteria weightings under a vague environment.

1.2 Aims and Objectives

The purpose of this research is to establish a mathematical framework for selecting the best trade-offs alternatives for regulatory compliance towards emissions reduction from shipping. The proposed approach is an efficient and effective decision framework for shipowners to make rational decision in terms of evaluation and selecting the most suitable alternatives in order to meet the emission reduction legislations.

1.3 Research questions

In order to achieve above-mentioned objectives, the research will attempt to answer an array of questions as follows:

a) How can shipowners and operators deal with stricter legislation regarding emissions from shipping?

b) Which compliance options or alternatives are available for shipowners to meet these regulations?

c) Which criterion should be considered when assessing those alternatives?

d) How can decision-makers can overcome the problem of vague and inconsistent information when evaluating aspects and criteria for the selection of alternative measures for regulatory compliance?

1.4 Methodology

Both quantitative and qualitative methodologies are used with literature review of similar research. The study develops an integrated fuzzy MCDM method by combining two techniques namely fuzzy AHP and fuzzy TOPSIS. To be more specific, the fuzzy AHP is employed to determine the important weights of aspects and criteria under vague environment. It is noteworthy that economic, environmental and social aspects are considered for the purpose of sustainability evaluation of alternatives. Afterwards, the fuzzy TOPSIS is used to prioritize and assess the alternative technologies for meeting requirements regarding emissions reduction from ships.

Qualitative methodology is also employed in this research by asking questionnaires to shipowners and operators to answer on their preferences for important weights of selected criteria and ratings of the alternatives with respect to criteria. Firstly, they will be asked to make pairwise comparison in respect of the different criteria using fuzzy linguistic variables. Afterwards, they will rate the performances of each alternative according to each criteria by expressing their opinions based on linguistics rating scale.

The integrated fuzzy AHP and fuzzy TOPSIS methodology will be discussed in more detail in the chapter 4.

1.5 Expected results

A generic framework is expected to be developed in order to assist shipowners and operators in selecting the best trade-offs alternatives in order to abide by the concurrent and upcoming emission reduction regulations. Three spheres of sustainability including social, economic and environmental viewpoint are mentioned for an evaluation of alternative technologies for emissions reduction due to shipping. Four feasible alternatives for emissions reduction from ships, including low sulphur fuel, HFO with scrubbers, LNG and Methanol are considered in the proposed approach with the aim of prioritizing the best suitable solution.

1.6 Outline of the thesis

Chapter 2 presents the overview on air emissions from shipping followed by the literature review in chapter 3. Afterwards, chapter 4 discusses the methodology with the proposed integrated MCDM approach by the combination of two techniques fuzzy AHP and fuzzy TOPSIS with the aim of establishing a ranking model for the selection of technologies for regulatory compliance towards emissions reduction from shipping. The proposed framework then is exemplified with case study in chapter 5. Finally, the discussion and conclusion are presented in the last chapter.

Chapter 2. Air emissions from shipping

Air pollution comprises a number of substances ranging from visible particle of smoke to invisible gaseous molecules of sulphur and nitrogen oxides. Recently, air pollution is one of the most heated issues concerning a large number of authorities, individuals at the local, regional and global levels. The statistics from the World Health Organization indicated that around 7 million people died attributed to air pollution exposure (WHO, 2014).

The emissions from shipping nowadays are recognized and considered on local, regional and global scales since emissions could be transported in the atmosphere from sea to land and over continents (Lonati et al., 2010). The emissions to the air from shipping exert detrimental impacts on the environment, climate and human health. Emissions consists of climate-related or greenhouse gases such as CO_2, methane (CH_4) and nitrous oxide (N_2O) and halogenated hydrocarbons. Emissions of SO_x and NO_x give rise to acidification of land and sea areas and formulate secondary particles. Moreover, NO_x leads to eutrophication and along with volatile organic compounds (VOCs) cause the formation of ground-level ozone which deteriorates the environment and human health. SO_x, NO_x and PM also have severe effects on human health resulting in respiratory and cardiovascular diseases and thus reducing life expectancy. Particles in different forms negatively impacts on the climate (Andersson et al., 2016).

International shipping is responsible for contributing global anthropogenic emissions, representing about 3%, 5-10% and 15-30% CO_2, SO_x and NO_x emissions respectively (Buhaug et al., 2009; Dalsøren et al., 2009; Eide & Endresen, 2011; Corbett & Koehler, 2003; Eyring et al., 2005; Wang et al., 2009). Corbett et al. (2008) forecasted the baseline scenario that air pollution resulted from global shipping activities would create up to 80000 premature mortality each year by 2012, in which the worldwide consumption of heavy fuel oil with average sulphur content of approximately 2.7%. For “coastal scenario”, the usage of distillate fuel with sulphur content of 0.1% by vessels operating within 200 nautical miles near the coastlines can contribute to the reduction of premature death rates by half, which accounts for 42 200 people in comparison with 60 000 in 2002. A more positive situation, or “global scenario”, which indicates that with a 0.5% sulphur cap in fuel content, the early death rate may be reduced by about 60% to 33700.

Johansson et al. (2017) depicted the high-resolution global spatial distributions of the shipping emissions of SO_x, PM2.5 by developing Ship Traffic Emission Assessment Model (STEAM3) so as to evaluate global emissions from international shipping for the year 2015. The effects of SECAs areas are clearly visible in the figure 2 and 3 where emissions densities in ECAs are lower than that in non-ECAs.

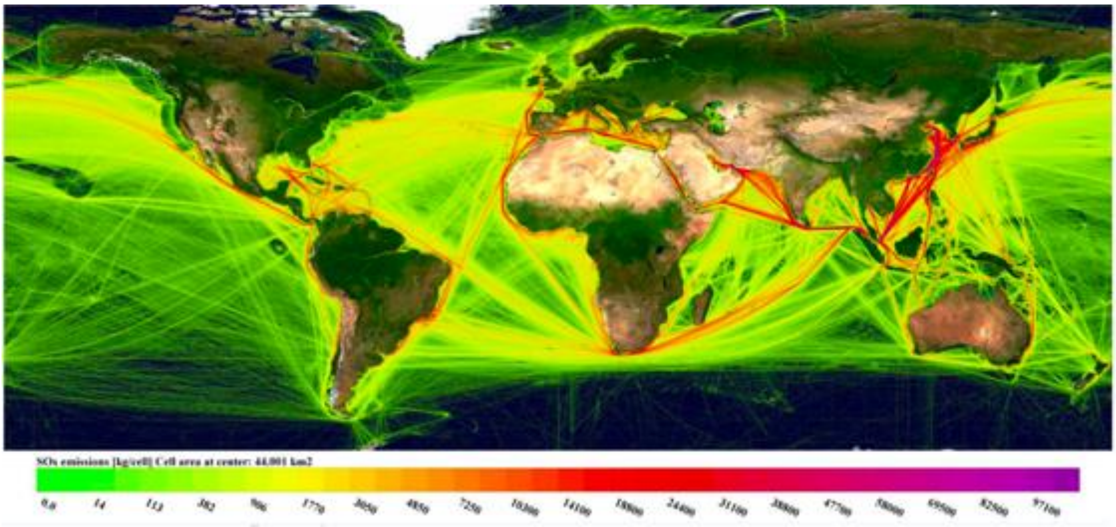


Figure 2. Geographical distribution of total SO_x emissions from global activities of shipping in 2015

Source: Johansson et al. (2017)

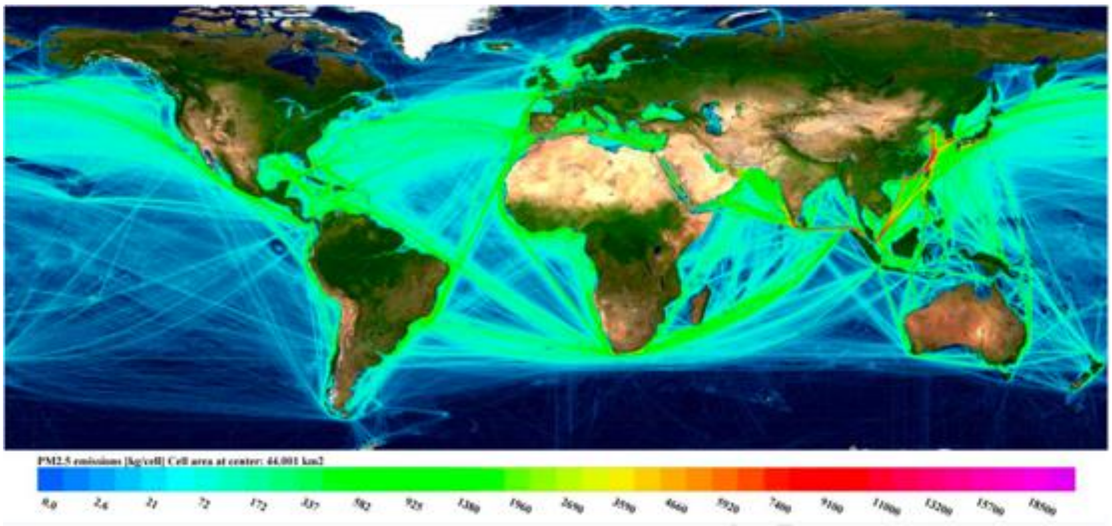


Figure 3. Geographical distribution of total PM2.5 emissions from global activities of shipping in 2015

Source: Johansson et al. (2017)

The figure 4 to figure 7 illustrate the diffuse emissions of sulphur dioxide (SO_2), NOx, CO2 and PM caused by international shipping of the EU27 and EFTA4 countries per 5x5 km^2 grid cell for the reference year 2008. Diffuse emissions of pollutants are demonstrated in tonnes per grid cell or kilotonnes per grid cell.

The environmental data provided by The European Pollutant Release and Transfer Register (E-PRTR) give the insights into the effects of different emissions from shipping sector on coastal Europe.

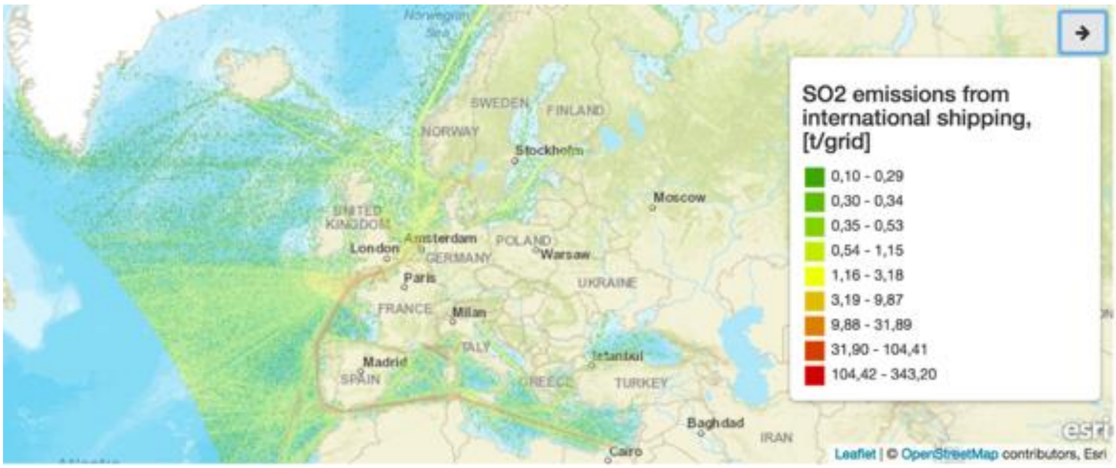


Figure 4. SO2 emissions from international shipping

Source: http://prtr.ec.europa.eu/

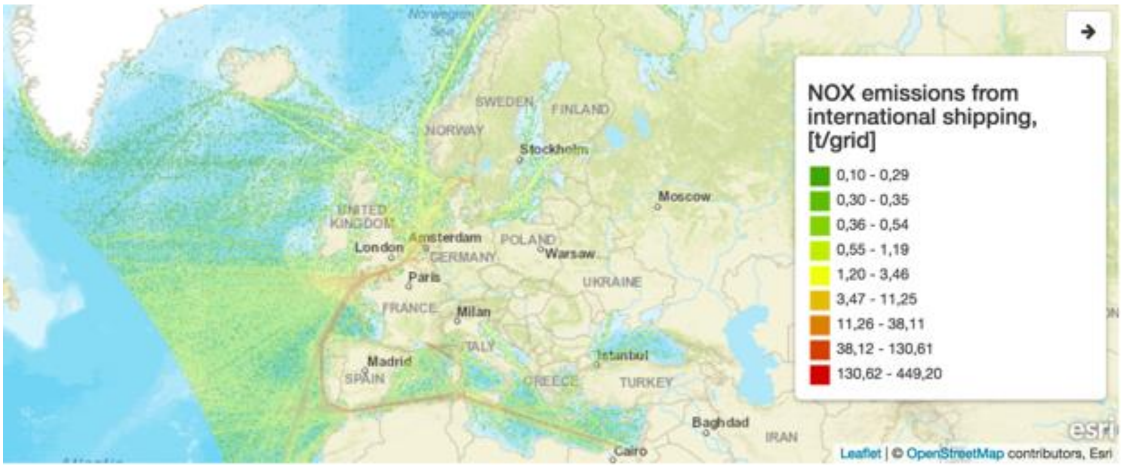


Figure 5. NOx emissions from international shipping

Source: http://prtr.ec.europa.eu/

Figure 6. CO2 emissions from international shipping

Source: http://prtr.ec.europa.eu/

Figure 7. PM10 emissions from international shipping

Source: http://prtr.ec.europa.eu/

2.1 Sulphur dioxides (SOx)

The abbreviation SO_x normally refers to sulphur dioxide (SO_2) and sulphur trioxide (SO_3), despite the fact that almost all sulphur is emitted as SO_2. For many years, SO_2 together with nitrogen oxide (NO_x) and ammonia (NH_3) are the air pollutants that result in acidification. Currently, the sulphate particles arising from atmospheric formation from SO_x emissions bring about negative effects on human health, visibility and climate (Vestreng et al., 2007).

The figure 8 gives information about global anthropogenic SO_x emissions from regions and international shipping between 1850 and 2010. As can be observed from the graph, there was a sharp rise in SO_2 emissions to air from international shipping (the black line) in the period from 1990 to 2010. Noticeably, SO_x emissions from international shipping in 2010 were higher than emissions from North America and Europe regions.

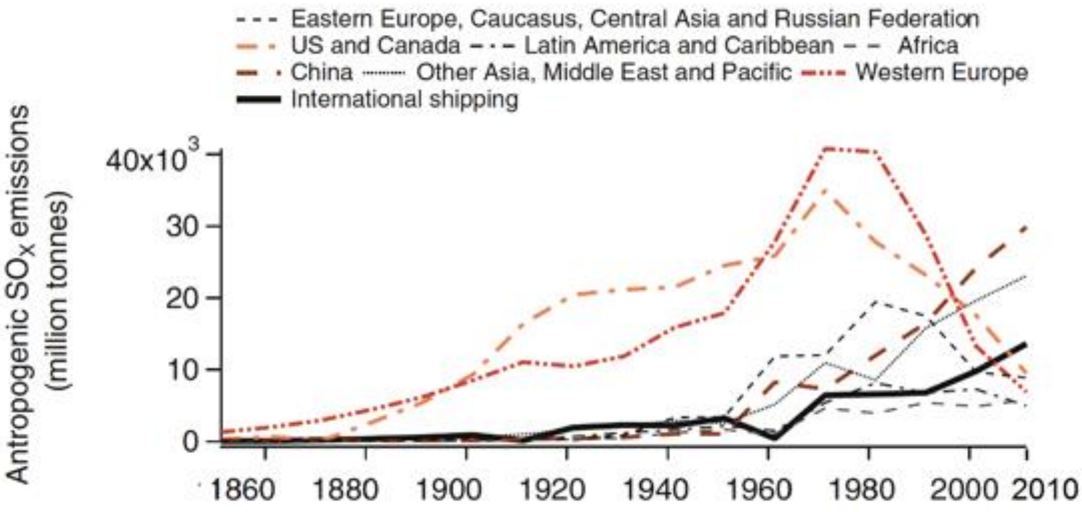


Figure 8. Global anthropogenic SO_x emissions from regions and international shipping from 1850 to 2010

Source: Andersson et al. (2016), data from 1850-1990 (Smith et al., 2011); data from 1990-2010 (Klimont et al., 2013)

In 2007, around 70% ships used heavy fuel oil (HFO), the remainders run on distillate oil fuels or marine gas oil (Buhaug et al., 2009). In the past, due to the lack of exhaust gas cleaning system on board, the amount of SO_x emissions from ships mainly depended on the content of sulphur in fuels. This is the reason for the increased SO_x emissions illustrated in the figure 8.

In response to the growing awareness on SO_x emissions from ships, the IMO regulated SO_x emissions in the regulation 14 of the MARPOL 73/78 Annex VI which sets a global limit on the sulphur content of marine bunker fuels and more stringent limit in ECAs. Given the revision of Annex VI, the sulphur limit was to be decreased progressively in the period of 2010 to 2020, as shown in figure 9. Initially, sulphur limits for bunker fuels worldwide was cut from 4.5% to 3.5% on 1 January 2012. The IMO has recently decided to implement a new global sulphur cap of 0.5% on marine fuels from the start of January 2020. Regarding SO_x regulations in ECAs, the current maximum sulphur content of fuel oil used by vessels is 0.1%, which has been in effect since 1 January 2015.

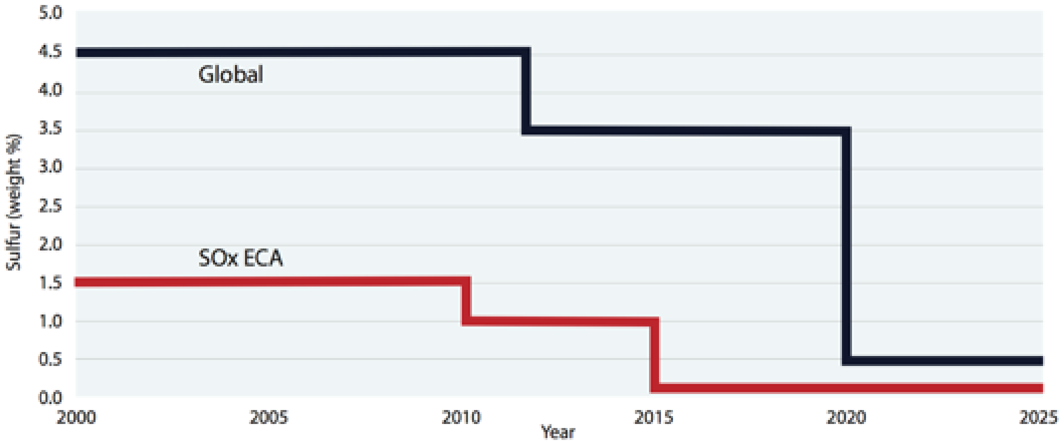
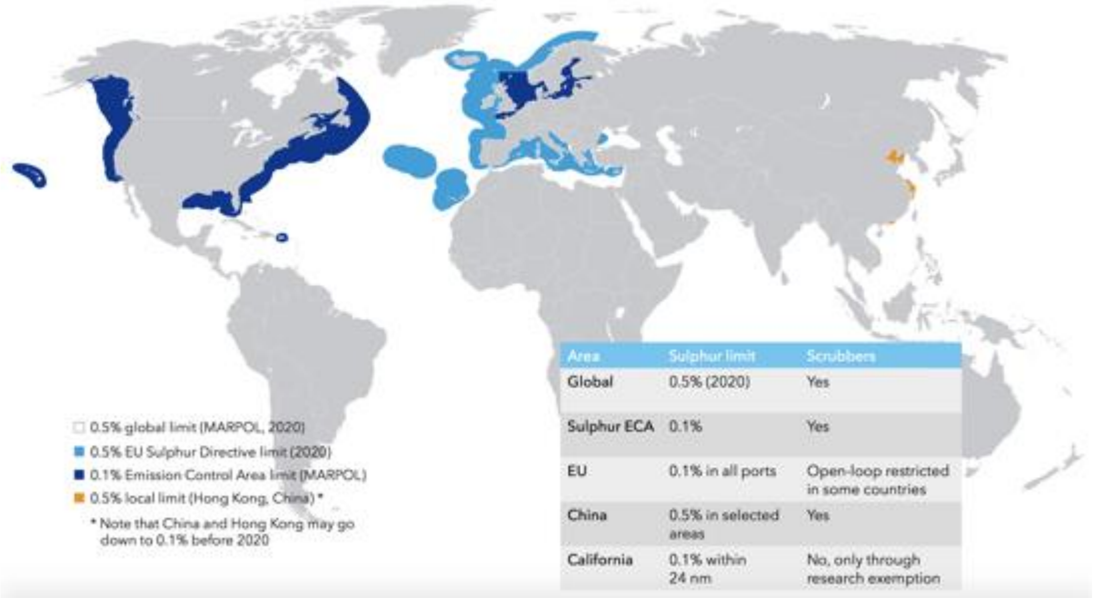


Figure 9. Present and future sulphur regulations

Source: www.imo.org

Furthermore, the sulphur requirements have also been designated to regional and local areas as shown in figure 10. The 0.5% sulphur content limit starting from 2020 for ships operating in all EU waters has been spelled out by the Directive 2012/33/EU. All passenger ships in EU non-ECA waters are still regulated to use fuel with a maximum sulphur content of 1.5% until 2020. Before that, the Directive 2005/33/EC introduced regulations on the sulphur content in marine fuel with a limit of 0.1% applying for ships at berth in EU ports since 1 January 2010. Recently, Hong Kong has a maximum 0.5% sulphur content for vessels at berth while China has introduced domestic SECA-like areas outside Hong Kong/ Guangzhou and Shanghai, and in the Bohai Sea with a cap 0.5% sulphur content in fuel burned in ports area and may go down to 0.1% before 2020. California’s Air Resources Board (ARB) imposes a maximum 0.1% sulphur within 24 nautical miles of the Californian coast (DVL GL, 2016).



Area	Sulphur limit	Scrubbers
Global	0.5% (2020)	Yes
Sulphur ECA	0.1%	Yes
EU	0.1% in all ports	Open-loop restricted in some countries
China	0.5% in selected areas	Yes
California	0.1% within 24 nm	No, only through research exemption

Figure 10. Sulphur content limits requirements

Source: DVL GL (2016)

2.2 Nitrogen oxides (NO_x)

Nitrogen oxide (NO_x) are normally described as the total of nitrogen monoxide (NO) and nitrogen dioxide (NO_2). When NO_x is emitted into the air, it gives rise to a range of various environmental effects such as acidification, eutrophication (Pleijel, 2009). In addition, NO_x is associated with the formation of ground-level ozone and secondary particulate matter (WHO, 2006). European Commission (2014) stated “NO_x emissions from international shipping are a direct contribution to eutrophication of inland and marine waters and terrestrial habitats, and to the formation of secondary particulate matter affecting health”. Eyring et al. (2010) estimated that NO_x emissions from international shipping rose from 12 to 20 Teragram/year in the period of 1990 to 2006.

NO_x emissions from shipping industry are regulated in Regulation 13 of the Revised MARPOL 73/78 Annex VI by the IMO. This regulation is defined by three separate NO_x emissions levels namely Tier I, Tier II and Tier III, which are shown in table 3.

Table 3. Regulation 13 Revised MARPOL Annex VI for NO_x limit

Regulation		Total weighted cycle emissions limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
Tier I	Diesel engines (>130 kW) installed on ships constructed on or after 1 January 2000 and prior to 1 January 2011	17.0	$45 \times n^{(-0.2)}$ e.g., 720 rpm – 12.1	9.8
II	Diesel engines (>130 kW) installed on ships constructed on or after 1 January 2011	14.4	$44 \times n^{(-0.23)}$ e.g., 720 rpm -9.7	7.7
III	Diesel engines (>130 kW) installed on ships constructed on or after 1 January 2016 (applies only in ECAs)	3.4	$9 \times n^{(-0.2)}$ e.g., 720 rpm - 2.4	2.0

Source: www.imo.org

Tier III which represents NO_x reduction of about 80% in comparison with Tier I, applies only in ECAs (except for the ECAs in the Baltic Sea and the North Sea). However, the Baltic Sea area and the North Sea area are considered to be designated as NO_x ECA by the IMO in the MEPC 71 Meeting. These ECAs will take effect from 1 January 2021 (IMO, 2017).

2.3 Greenhouse gas (GHG)

The impact of Greenhouse gas on climate change are discussed and negotiated at global level within the United Nations Framework Convention for Climate Change (UNFCCC). The shipping sector associated with GHG emissions was handled in global discussion through the Kyoto Protocol. GHG emissions from international shipping is not included in the Kyoto Protocol, however, treated as a separate entity. Countries were assigned to pursue reduction and limitation of GHG emissions from shipping through the IMO. Considering the appropriate contribution of international shipping to global efforts to reduce GHG emissions, the IMO has made clear that “the shipping industry will make its fair and proportionate contribution” (Anderson & Bows, 2012; Mander, 2016).

There are several mechanisms produced by the IMO aiming to reduce GHG emissions from shipping via both technical and operational aspects. In the first place, the IMO has introduced two measures towards energy efficiency called the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Management Plan (SEEMP). The first measure is a goal-based technical standard applicable to new-build vessels from 2013 whereas the latter encourages shipping companies to have a plan on board each vessel in order to improve the energy efficiency during its life-cycle operation (Bazari, 2016). Furthermore, the IMO has recently adopted a new regulation 22A in MARPOL Annex VI on data collection system which requires vessel to record and report their annual fuel consumption and other related data. The MEPC 70 Meeting approved a Roadmap for the development of a “Comprehensive IMO strategy on reduction of GHG emissions from ships” (IMO, 2016). It is expected that the initial strategy will be adopted in 2018 then will be revised in 2023 to include measures with implementation schedules.

The EU has also introduced its own regional policy regarding monitoring, verification and reporting (MRV) which is planned to start from 2018. Under the MRV regulations, ship operators will be responsible for making a monitoring plan and then giving an annual report, all subject to verification by an designated body (European Union, 2015). In the longer run, the EU plans to integrate the strategy with a market-based measure (Emissions Trading Scheme) for reducing GHG emissions. The EU has set the target of 40% reduction in carbon emissions from maritime transportation compared with 2005 levels by 2050 (European Commission, 2011).

2.4 Particles

Generally, emissions of particles refer to emissions of particulate matter (PM). There are expressions of PM are PM10 and PM2.5 which mention the aerodynamic diameter of particles less than 10 and 2.5 μm, respectively. It was estimated that about 95% PM emissions generated from ships is of PM2.5 (Sharma, 2006). Corbett et al. (2007) pointed out that emissions of PM from shipping sector resulted in around 60,000 cardiopulmonary and lung cancer mortality rate globally in 2002, and this figure increased by 40% by 2012 attributed to the development of the maritime transportation. Nonetheless, there are still no specific regulations for PM emissions from international shipping. Since oxidised sulphur from marine fuel leads to the formation of new particles, PM emissions are viewed as indirectly regulated by SO_x regulation which was discussed in previous section.

Chapter 3. Literature review

3.1 Review on MCDM models

It can be well-observed in the literature review that MCDM problem is applied in various fields such as engineering, economics, etc. MCDM aims to achieve ideal and applicable results in problems which are difficult to model and for which views of experts are required. From a methodological viewpoint, decision making process could become highly complicated when evaluating alternatives with regard to criteria that potentially structuring the decision process (Özdemir & Güneroğlu, 2015). The task is to choose among a set of finite number of alternatives associated with multiple criteria evaluation so as to select the best alternative which is the best trade-offs or a compromise resolution. In other words, after criteria evaluation and assessment, alternatives are ranked from the best to the worst. There are a wide range of MCDM methods in literature review specifically in energy field such as the ELECTRE (Elimination and Choice Translating Reality) method (Jun et al., 2014) and modified-ELECTRE method (Mousavi et al., 2017), DEA (Data Envelopment Analysis) method (Ren et al., 2014; Mardani et al., 2017; Feng et al., 2017), the VIKOR (Viekriterijumsko Kompromisno Rangiranje) method (Kaya & Kahraman, 2010; Ren et al., 2015), PROMETHEE (Preference Ranking Organization Method For Enrichment And Evaluations) method (Ren et al., 2015) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method (Özcan et al., 2017). Additionally, there are also several techniques for assigning the weights of criteria such as WET (Weighted Evaluation Technique), CRITIC (Inter-Criteria Correlation) method, ANP (Analytic Network Process), FQD (Fuzzy Quality Function Deployment) and fuzzy AHP (Analytic Hierarchy Process).

In the view of environmental assessment of different solutions for the emissions reduction from ships towards greener or cleaner seaborne transportation and eventually sustainable shipping, literature has experienced full of studies applying cost-benefit analysis which is a single dimensional point of view. However, there is little studies undertaking MCDM approach for assisting decision-makers to select the best trade-offs solution. The MCDM method based on the ANP technique was established by Schinas and Stefanakos (2014) as decision-making tool in selecting the technologies in order that operators can comply with MARPOL Annex VI regulation. By using a subjective generic methodology, Yang et al. (2012) developed an evaluation model for ship owners to select their preferred NO_x and SO_x control techniques. Ölcer & Ballini (2015) proposed a comprehensive decision-making framework evaluating the trade-off solutions of cleaner seaborne transportation with a case study in the Port of Copenhagen, Denmark utilising cold-ironing technology. In their research, they employed TOPSIS method for ranking the best compromise solution. The research work of Ren & Lützen (2015) presented a generic model which incorporates the fuzzy AHP and VIKOR techniques to prioritise and select the emissions reduction alternative technologies for ships. Wang & Nguyen (2016) developed an integration of FQFD and FTOPSIS method for prioritizing mechanism of low-carbon shipping measures. Recently, Ren & Lützen (2017) proposed a MCDM method by combining Dempster-Shafer theory and the trapezoidal fuzzy AHP for the selection of sustainable alternative energy source for shipping.

Indeed, it is challenging for decision-makers to make wise decision by dint of the imprecision which comes from unquantifiable, inaccurate, incomplete information (Ölçer & Odabaşi, 2005) or the lack of knowledge (Liu and Huang, 2012). In contemporary maritime sector, the decision makers are dealing with MCDM problem which has multiple criteria and alternatives with uncertain and incomplete information. The previous MCDM studies do not carry out well on selecting the best measure for shipping for environmental compliance owing to the complexity of criteria-weightings determination under a vague environment. There is a room for improvement on previous studies on the selection of the best technologies among multiple alternatives aiming at reducing emissions from shipping. The classical AHP introduced by Saaty (1980) identifies the alternatives or the criteria weightings by utilizing a hierarchical model including target, major criteria, sub-criteria and alternatives. However, the main drawback of AHP is that the application of a discrete scale of 1-9 could not determine the priorities of different criteria precisely by virtue of imprecision and uncertainties of human thinking. The fuzzy set theory introduced by Zadeh (1965) is an powerful tool for handling problem of imprecision and vagueness. The fuzzy AHP has been deployed in order to overcome the ambiguity and vagueness of human judgments on the accuracy of criteria weights. The fuzzy AHP method is a combination of classical AHP and the fuzzy set theory depicting human perception and preferences as linguistic emphasis and fuzzy numbers. In recent years, TOPSIS method first proposed by Hwang & Yoon (1981) has been broadly used to solve MCDM problem. In the literature, TOPSIS has been applied to 266 published papers, covering a variety of research fields (Behzadian et al., 2002). The fundamental principle of TOPSIS is to choose alternatives by measuring their Euclidean distances to the positive ideal solution (PIS) and negative ideal solution (NIS). The chosen alternative is an alternative that have the shortest distance from the PIS and furthest distance from the NIS. The positive ideal solution maximizes the benefit criteria and minimizes the cost criteria. On the contrary, the negative ideal solution maximizes the cost criteria and minimizes the benefit criteria. In the process of the classical TOPSIS approach, criteria weightings and ratings of alternatives are described as crisp values which are unable to handle vagueness and lack of information in many real-life cases. As a result, an enhanced variant of TOPSIS namely fuzzy TOPSIS is proposed to deal with this problem by means of evaluating the weights of criteria and ratings of alternatives by linguistics variables depicted by fuzzy numbers. There are several benefits of the TOPSIS and fuzzy TOPSIS technique. In the first place, human choices and preferences are embodied in the logical way. In addition, they can be computed easily due to their simple programming process. Moreover, the number of stages in the method remains the same irrespective of the number criteria or attributes. A further advantage is that they reveal a scalar value that represents both the best and the worst alternatives at the same time (Fu et al., 2007).

In literature, several studies have used either fuzzy AHP or fuzzy TOPSIS approaches to address MCDM problem in many areas of research. Nevertheless, few studies have proposed method that combines two techniques, especially in the case of choosing technological measures to reduce emissions from ships. In this research, an integrated MCDM approach is developed in order to address a problem of technological solutions for shipping for regulatory compliance by utilising fuzzy AHP in combination with fuzzy TOPSIS. Specifically, important weights of criteria under ambiguous environment are determined by the fuzzy AHP, the fuzzy TOPSIS then is employed to evaluate and prioritise the alternatives.

3.2 Criteria for sustainability assessment for technological alternatives

In the purpose of prioritizing technological alternatives for regulatory compliance for shipping, the selection of aspects takes into account of sustainability assessment in which proposed criteria are defined within three aspects regarded as three pillars of sustainability: economic performances, environmental effects and social impacts. This is the concept of sustainable development aiming at achieving economic prosperity, environmental health, and social responsibility simultaneously. The three different spheres of sustainability are shown in figure 11 (Andersson et al., 2016).

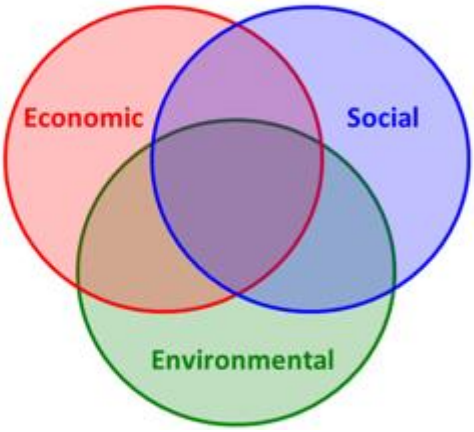


Figure 11. Three pillars of sustainability

Source: Adapted from Andersson et al. (2016)

In the scope of this study, nine criteria in three aspects based on literature review such as technical reports and scientific publications are selected as specified in Figure 12. There are three criteria in the economic aspect, including capital cost (CAPEX), operational cost (OPEX) and life-cycle cost. The environmental aspect comprises the impact on SO_x emissions reduction, NO_x emissions reduction, GHG emissions reduction, and PM emissions reduction. Externalities and government and industry support are criteria belonging to social aspects. It should be noted that all assessment aspects are generally of conflicting and trade-off nature and proposed criteria are dependent on the judgement and preferences of decision-makers which means that they can add or delete criteria in each aspect based on the actual situations. There are several realistic alternatives in the search for alternative compliance measures for ships: using low sulphur marine fuels such as marine gas oil (MGO) or marine diesel oil (MDO) in the current machinery; integrating an emission abatement technology such as marine scrubber as an after treatment device; opting for operating on LNG or running on Methanol as fuel (ABS, 2017; Dalaklis et al., 2016; IMO, 2016; Schinas & Butler, 2016; Ellis & Tanneberger, 2015). The decision-makers are facing today with the task in considering aforementioned criteria in order to select the most suitable option among multiple alternatives.

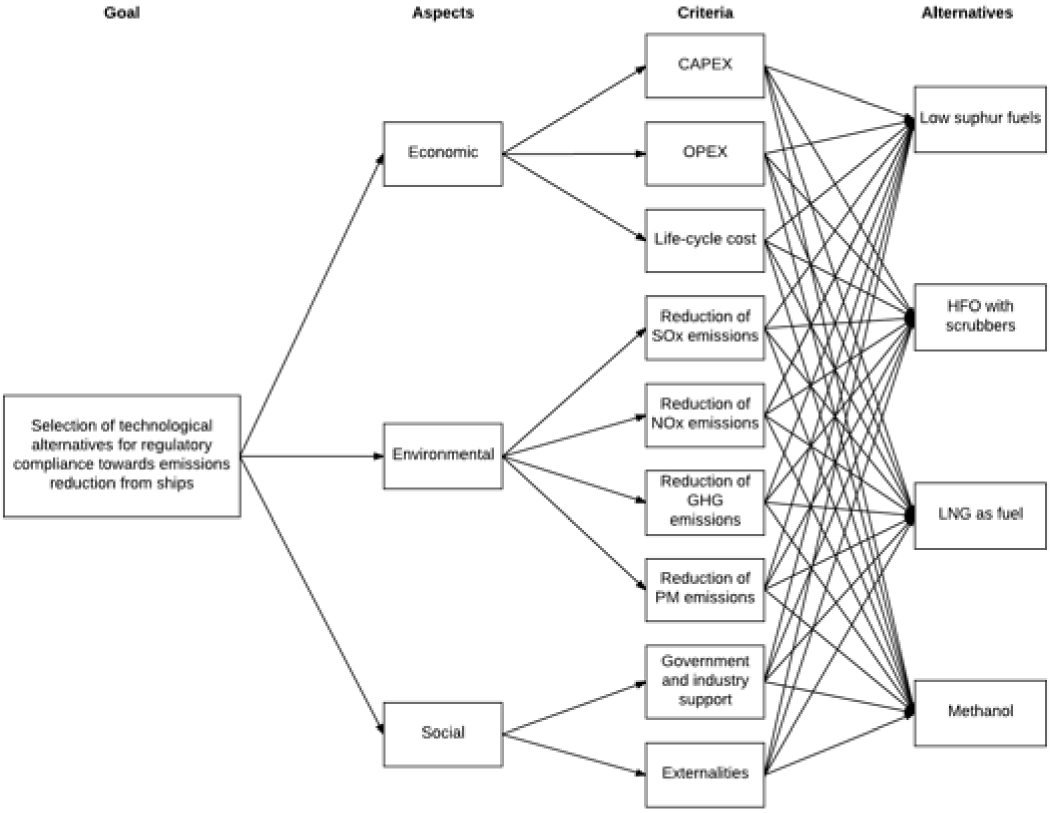


Figure 12. Decision hierarchy of the selection of trade-offs alternatives for regulatory compliance towards emissions reduction from shipping

3.2.1 Economic aspect

3.2.1.1 Capital cost (CAPEX)

The capital cost refers to the total costs for the retrofitting of existing ship to operate new alternative fuel or the total costs for the installation of new technological devices on board such as exhaust gas cleaning system (scrubber). In other words, the capital costs consist of the costs for system components, engine retrofit and engine room modifications (Deniz & Zincir, 2016). The cost for engine conversion depends on type and dimensions of the vessel.

The capital costs for low-sulphur marine fuels, generally referring to as compliant fuels or distillates are considered to be negligible since the vessel engines can operate on both heavy fuel and low sulphur fuel (Helfre & Boot, 2013). In addition, low-sulphur fuels incur the lowest investment costs compared to that of marine scrubbers installation or the utilisation of LNG as demonstrated in table 4. This is due to the fact that the modifications to the ship using low-sulphur fuels are smaller in comparison with remaining cases and low-sulphur fuels are generally available around the world. However, the problem with low-sulphur fuel is that the stringent sulphur content regulation and the introduction of more ECAs could result in an increase in a price of low-sulphur fuel (Acciaro, 2014).

Meanwhile, the investment of a scrubber on board is similar to the installation of other ship machinery in newbuilding ships. The capital costs of scrubber range from € 2 to 8 million per ship, depending on the ship type and scrubber type (OECD/ITF, 2016). The system price per maximum washed power (€/MW) is a typical parameter of investment cost estimation. This parameter can be applied only for similar type and size of vessels. The installation cost of a retrofit scrubber is different from that of a new-building (Lahtinen, 2016). Boer & Hoen (2015) estimated that the installation cost lies in a range from 0.2 to 0.4 €/MW for retrofit installations and from 0.1 to 0.2 M€/MW for newbuildings.

Table 4. Comparison of investment costs of scrubber and LNG options with that low-sulphur fuels

Economic aspect	Scrubber	LNG
Investment costs (new-building)	-	-/-
Investment costs (retrofit)	-	--

Source: Adapted from OECD/ITF (2016).

Currently, the capital investments of LNG-fuelled ships are higher than the combination of exhaust gas cleaning systems and selective catalytic reduction (SCR) systems (Acciaro, 2014) and higher than that of a ship running only on diesel fuel (IMO, 2016). To be specific, the capital expenses for new-building ships equipped with LNG propulsion are around 10-20% higher in comparison with traditional drive systems (Simmer et al., 2014), estimated to be € 4-6 million based on some findings (EMSA, 2010). However, Carr and Corbett (2015) speculated much higher estimations that the LNG-retrofit cost of a 19 000 tonnes Great Lakes bulk carrier would be USD 24 million and the conversion costs of Panamax and Post-Panamax container ships would be higher since they have larger engines. Another statistics based on the prediction of DNV showing that the initial capital expense of a new LNG-fuelled vessel will increase 10–50% (Helfre & Boot, 2013). As a result of considering this cost, LNG conversion is not regarded to be cost-competitive option compared to fuel switching or open-loop scrubbers (OECD/ITF, 2016).

Regarding the economic viewpoint towards Methanol conversion cost, it is considered as feasible solution as methanol is easy to handle with slight modifications (Stefenson, 2015). In the report carried out by EMSA, it is estimated that the retrofitting and new-build installing costs for both methanol and ethanol fueled vessels are equivalent to costs for installing scrubber and SCR technology for use with HFO and below LNG investment costs (Ellis & Tanneberger, 2015). The main reference point on Methanol retrofitting cost comes from the conversion of the 24 MW ro-pax ferry Stena Germanica. The cost for conversion was € 13 million and the total cost of the Stena Germanica project was € 22 million including infrastructure and preparation costs such as a methanol storage tank onshore and bunker barge adaptation. Because of the fact that Stena Germanica project was the pioneer of its kind, all new technical solutions, risk assessment, adaptation of requirements and regulations were taken into account in this project. It is highly considerable that the cost for subsequent retrofits would be around 30% to 40% lower than the first project (Stefenson, 2015; Andersson & Salazar, 2015).

Figure 13. Payback time for retrofitting a 24 MW ferry at price differences between Methanol and MGO

Source: Andersson & Salazar (2015)

In comparison with the competitive counterparts, Methanol investment costs are lower than that of LNG as apparently shown in figure 13. To be specific, the conversion cost of M.V. Stena Germanica to operate Methanol was about 350 €/kW meanwhile the retrofitting cost of BIT Viking for running on LNG was 1000 €/kW (Stefenson, 2015). When the technology is mature, the cost of a new-built methanol-fueled vessel is predicted to be equal to that of a traditional vessel running on HFO. For example, it is unnecessary to install fuel heating and oil separators when using Methanol as fuel since it is clean fuel and easily pumped at ambient temperature (Andersson & Salazar, 2015).

3.2.1.2 Operational cost (OPEX)

Operational costs comprise fuel price, maintenance costs, and consumable costs. Maintenance costs are associated with engine maintenance intervals. Another factor affects maintenance costs is system complexity (Deniz & Zincir, 2016). It is estimated that using methanol as fuel will shorten maintenance intervals and opting LNG leads to wider maintenance intervals. Tawfek et al. (2007) indicated that maintenance intervals would be increased three to four times when using natural gas as fuel at diesel engines diesel fuel operation.

Dual fuel engines enable vessels to be run on either conventional fuels (MGO, HFO) or LNG. Fuel switch can be made smoothly during operation without loss of speed or power, allowing operator to choose the fuel according to actual condition in terms of cost and availability. However, the maintenance for dual-fuel engines requires more than that of single traditional fuel engines, resulting in slightly higher maintenance costs (Wärtsilä, 2017). The use of LNG as an alternative is considered as economically feasible in the short and medium run due to operational pattern, fuel cost and availability of natural gas all over the world. The purchase price of LNG at the end of 2016 was about 6,1% lower than that of HFO (Wärtsilä, 2017). Although the price of natural gas is lower than that of diesel fuel, especially in the North America, the future prices of LNG are unpredictable since the global market for natural gas is unavailable and infrastructure for LNG marine bunkering is still under scrutiny (IMO, 2016).

The maintenance costs of methanol are estimated to be in the same range or even lower than that of traditional fuels. Besides, Methanol is more competitive when compared with scrubbers since the latter also add to operational costs. The operational costs of a vessel are mainly fuel costs, accounting for 50% or more (Andersson & Salazar, 2015). As shown in figure 14, in the period from 2010-2014, the price of methanol was low in comparison with marine diesel. With the current low oil prices market in 2015, marine diesel prices have decreased significantly, which undermining the methanol rate advantage. Exceptionally, methanol price in China was the most affordable among the two. The payback analysis undertaken by Ellis & Tanneberger (2015) concluded that methanol is competitive with other emissions compliant fuels but this depends on the fuel price differentials. According to historic price differentials, methanol is predicted to have shorter payback times than both LNG and ethanol solutions for fulfilling regulations in SECAs. In the recent low oil prices at the end of 2015, the conventional fuel oil alternatives have shorter payback times.

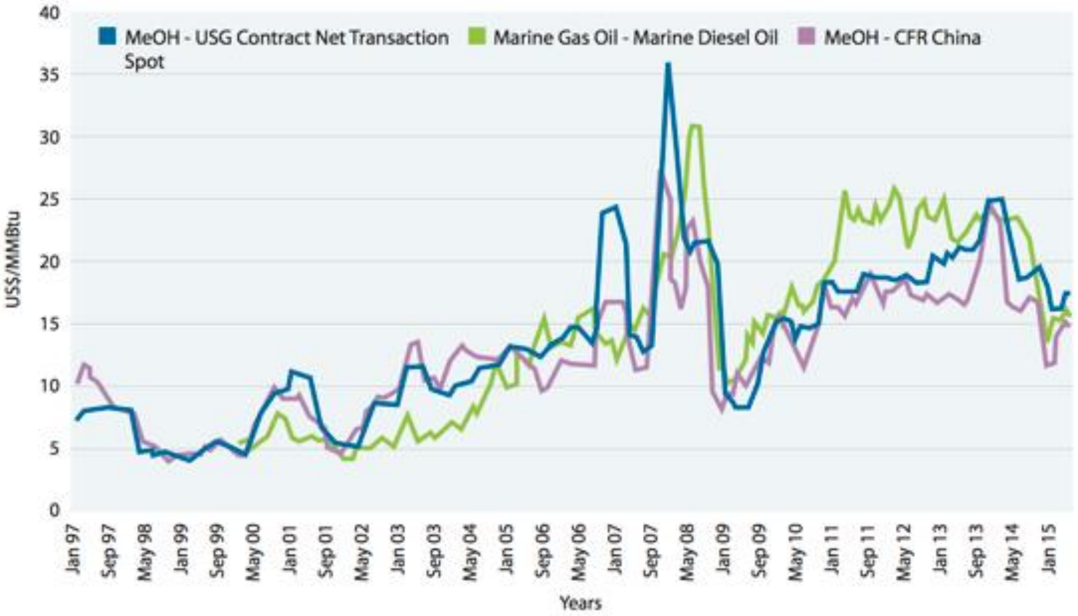


Figure 14. Methanol and MGO prices ($/MMBtu)

Source: Andersson & Salazar (2015)

Low sulphur in content or higher quality fuels are significantly more 30-50% expensive than the conventional heavy fuel oil commonly burned in the vessels (Notteboom, 2010; Acciaro, 2014), triggering a penalty of increased operational cost (IMO, 2016). For short-sea shipping only in ECAs, ships usually operate low-sulphur fuels all of the time. Other vessels tend to switch to low sulphur fuels when operating inside ECAs and using high sulphur fuels outside ECAs. It is predicted that the prices of low-sulphur fuels especially MGO and MDO will inevitably increase in the short-term if operators follow this pattern (DVL GL, 2016). The operational cost of shipping company is estimated to rise by approximately 87% attributed to the expense of refining and converting to low-sulphur fuel (Helfre & Boot, 2013). Nonetheless, using low-sulphur fuels results in cost-savings for shipowners and operators compared to HFO. This is due to the fact that distillate fuels have higher thermal value which reduces engine wear and requires less frequent maintenance. Another reason is that it has higher energy content which means lower fuel consumption. In addition, the use of distillate fuel also leads to less sludge on board, contributing to less maintenance (OECD/ITF, 2016). Table 5 draws the comparison of scrubber and LNG with low-sulphur fuels in terms of operational costs.

Table 5. Comparison of scrubber and LNG options with low-sulphur fuels

Economic aspect	Scrubber	LNG
Operational costs	+	-/+

Source: Adapted from OECD/ITF (2016).

In respect of marine scrubbers operating cost, it ranges from € 320 to 580 per tonne sulphur dioxide according to the findings of CNSS (2014). In addition, EMSA (2010) estimated that the increased fuel consumption is about 1-3% in the operation of scrubbers. Boer and Hoen (2015) stated that the operation and maintenance cost for scrubbers could be about 1-3% of capital cost per year. Regarding economy concern, using scrubbers is dependent on the oil price in the market. For instance, at 2015 prices, scrubbers were applied as alternatives for some applications. The handling of sludge from scrubbers could be taken into account since is not well-developed and may lead to higher cost in the future (Andersson & Salazar, 2015).

3.2.1.3 Life-cycle cost

The life-cycle cost refers to the total costs for building ships, fuel costs over the lifespan of a ship and other associated costs accumulated for a long-term time frame after being built (Afseth, 2013).

In the purpose of assessing the annual costs of scrubbers, Boer & Hoen (2015) investigated a case study on a new-built product tanker with 9,500 kW installed main engines and 2,900 kW auxiliary engines with operation pattern about 50% of the time in a SECA area. The comparison between running on MDO in the SECAs and installation of open-loop or closed scrubber was conducted. The results based on January 2014 fuel prices found that the annual cost when using HFO with an open scrubber was similar to that of operating MGO fuel meanwhile it was 25% higher if utilizing a closed-loop scrubber due to the additional use of chemicals for and higher investment costs. Considering the life-cycle cost, The Baltic and International Maritime Council (BIMCO) supposed that scrubber option is cheaper than low-sulphur fuel option in the longer term (Helfre & Boot, 2013).

Fuel costs will be cut considerably by opting LNG, which lead to the LNG overall life-cycle expenditure of LNG-fuelled engines lower than that of oil-fuelled ones, even considering higher capital and maintenance expenses. A study conducted by Shell and Wärtsilä indicated that there was a considerable life-cycle saving accomplished by small, medium and large ships using LNG as fuel in comparison with HFO (Wärtsilä, 2017).

3.2.2 Environmental aspect

In recent years, air emissions to air from shipping have paid much attention, focusing on SO_x, NO_x, PM and GHG emissions.

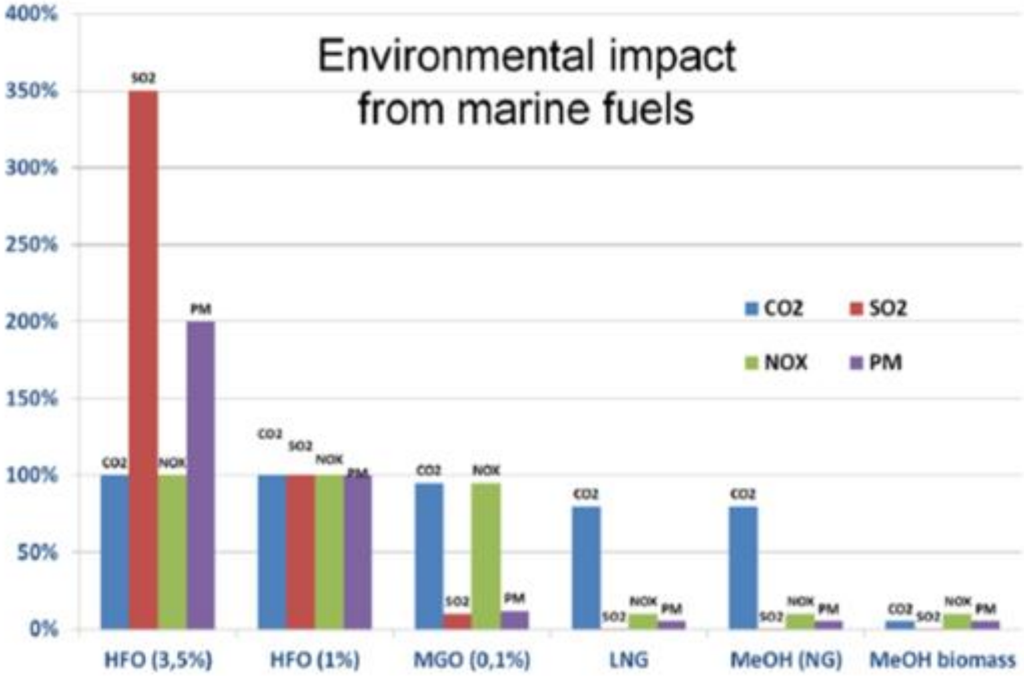


Figure 15. Environmental assessment of present and future marine fuels

Source: Brynolf (2014)

The research work of Brynolf (2014) used life-cycle analysis to assess the environmental impact of current and prospective marine fuels. She compared the environment impact of HFO with different marine fuels such as MGO, LNG, Methanol produced from natural gas and Methanol from biomass (forestry residues). It is clear from the figure 15 that both LNG and Methanol has positive impact on

SO_2, NO_x and PM emissions reduction as compared to HFO and MGO. It is noticeable that apart from SO_2, NO_x and PM emissions reduction, using Methanol from biomass will reduce significantly greenhouse gases emissions.

3.2.2.1 Impact on SO_x reduction

Due to the fact that SO_x emissions are directly proportional to the sulphur content of fuel, the use of fuels that have low sulphur in content such as MGO and MDO can contribute to lowering SO_x emissions while utilising HFO with integrating marine scrubber in the current propulsion system will reduce SO_x emissions to almost zero (CNSS, 2013). The use of LNG as a ship fuel emits virtually 0% SO_x emissions in comparison with the use of HFO as LNG does not contain sulphur (Burel et al., 2013). Likewise, Methanol is cleaning-burning and sulphur free fuel which emits very small SOx emissions (Ellis & Tanneberger, 2015).

3.2.2.2 Impact on NO_x reduction

With respect to NO_x emissions reduction, the approach towards meeting the stricter Tier III NO_x regulation is to have additional post treatment system and SCR is the most common technique where NO_x is reduced by an added reducing agent, normally ammonia or urea with a base metal catalyst (Burel et al., 2013; Brynolf et al., 2014). This technique has been proven able to combine with a number of marine bunker fuel such as HFO and can be used with different marine engines (Brynolf et al., 2014). Although scrubbers have possibilities for reducing NO_x emissions, there is no consensus on how much it could achieve (Helfre & Boot, 2013). Winnes (2017) stated in his review on marine scrubbers and environmental performance that the effects of scrubber on NO_x emissions reduction are not conclusive - ranging from 0% to 12% - and depend on the ratio $NO:NO_2$ in exhausts. By using HFO in combination with SCR and open-loop scrubber, the NO_x reduction could be reduced by 87% (CNSS, 2013) while Magnusson et al. (2012) concluded higher NO_x reduction could be reached, at the level of above 90%. Fuel switch to MGO only provides a reduction of a few percentage on NO_x emissions. However, using MGO with SCR can reduce NO_x emissions of 80%, compared to HFO engines (CNSS, 2013).

The use of LNG, compared to the use of HFO, has advantageous NO_X emissions reduction with the figure of about 80-85% as a result of the lean burn combustion process in dual fuel internal combustion engines (Burel et al., 2013).

NO_x emissions levels when switching to Methanol are low, in line with Tier III NO_x emissions (2-4 g/kWh) (Andersson & Salazar, 2015). Methanol emits NO_x emissions lower compared to that from conventional fuels, even though the amounts depend on the combustion concept and temperature (Ellis & Tanneberger, 2015).

3.2.2.3 Impact on GHG reduction

Both options of fuel switch to low-sulphur fuels and HFO with scrubbers have no effect on GHG emissions reduction. Besides, operation of scrubbers and SCR can give rise to increased fuel consumption (Helfre & Boot, 2013). On the other hand, opting for LNG could reduce CO_2 emissions by 20-30% owing to higher hydrogen content in molecules, compared to HFO/ MGO (Burel et al., 2013). Nonetheless, in the research on exhaust gases from an LNG fueled vessel, Anderson et al. (2015) found that around 85% of hydrocarbons emissions from LNG was methane (CH_4). At lower engine loads, the emissions of methane could be up to 15% (Nielsen & Stenersen, 2010). Methane slippage and spills during the handle and combustion of LNG may give rise to GHG contribution since CH_4 is a potent GHG (Andersson et al., 2016). As can be seen from the table 6, CH_4 has over 20 times higher of Global Warming Potential (GWP) which is used to quantify effectiveness of a greenhouse gas than that of CO_2 over a 100-year perspective.

Table 6. Global warming potentials of compounds

	Lifetime (year)	GWP over 100 years (kg CO_2 eq./kg)	GWP over 20 years (kg CO_2 eq./kg)
Carbon dioxide (CO_2)	-	1	1
Methane (CH_4)	12.4	28 (34)	84 (86)

Nitrious oxide (N_2O)	121	265 (298)	264 (268)
HFC-134a	13.4	3710 (3790)	1300 (1550)
CFC 11	45	6900 (7020)	4660 (5350)
CF_4	50,000	4880 (4950)	6630 (7350)

Source: Stocker et al. (2013).

Furthermore, based on the findings conducted by Brynolf et al. (2014), both LNG and Methanol produced from natural gas will not reduce the GWP in the life cycle. Nonetheless, Methanol produced from biomass has possibility to reduce GHG emissions from shipping.

3.2.2.3 Impact on PM reduction

Due to the fact that most of PM emissions from marine engines are connected with fuel sulphate contents, low-sulphur fuels give rise to lower sulphate formations and thus reduced PM emissions. The burning of LNG leads to negligible PM production (Burel et al., 2013; Helfre & Boot, 2013). Similarly, using Methanol also emits PM emissions at the negligible level as it contain no sulphur (Deniz & Zincir, 2016; Ellis & Tanneberger, 2015). In this regard, it is difficult to draw conclusions on effects of scrubber on PM emissions from the published studies. Several studies indicate no PM reduction when using scrubber while others specify up to 75% PM reduction. Reports from manufacturer organizations suggest large reductions of PM emissions (by mass) over scrubbers at the rates of 75-90% but it lacks transparency and detail (Winnes, 2017). According to Helfre & Boot (2013), the use of HFO with scrubber has significant reduction of PM emissions by at least 80%.

Table 7 presents the comparison of the environmental effects of compliant alternatives. The data have been consolidated from many sources as discussed in previous sections.

Table 7. Comparison of the environmental effects of compliance options

Environmental Aspect	HFO with scrubber	Low sulphur fuels	LNG	Methanol
Impact on SO_x reduction	SO_x emissions almost zero	Low SO_x emissions	SO_x emissions are almost completely eliminated	Negligible SOx emissions
Impact on NO_x reduction	Reduced NO_x emissions by scrubber still unknown. Need additional after treatment like SCR which reduces NO_x emissions by 87% and above	No significant impact (a few percentage on NO_x emissions reduction). MGO with SCR can reduce NO_x emissions of 80%, compared to HFO engines	Reduction of 80-85% NO_x emissions compared to HFO engines	NO_x emissions level is low, in line with Tier III NO_x emissions
Impact on GHG reduction	No decrease	No decrease	Reduction of 20-30% CO_2 emissions but produce Methane	Reduce GHG emission if produced from biomass
Impact on PM reduction	Significant reduction of PM content by 80%	Reduced PM emissions	PM production is negligible	PM production is negligible

Source: Adapted from Burel et al. (2013); CNSS (2013); Helfre & Boot (2013); Andersson & Salazar, 2015; Ellis & Tanneberger, 2015; Brynolf et al. (2014).

3.2.3 Social aspect

3.2.3.1 Government and industry support

This criterion expresses the attitudes of public and government support to the adoption of technological alternatives onboard the ships to meet emissions reduction standards and requirements. According to a study conducted by the Lloyd's Register in 2011, the likelihood is that LNG as ship fuel will be widely opted in the future due to its competitive market price. Through a survey on shipowners, the research also concluded that when it comes to compliance with sulphur emission regulations, low sulphur fuels are regarded as only a short-term solution whereas LNG as ship fuel is considered as a viable long-term solution for liner shipping such as container vessels (Lloyd's Register, 2012). Currently, it is likely that ships sailing on fixed routes (containerships, RoRo) and usually operating in ECAs tend to adopt LNG as a fuel (Burel et al., 2013; Acciaro, 2014). Meanwhile, Methanol is regarded as a very attractive fuel choice from both environmental and economic perspective (Ellis & Tanneberger, 2015). It has been used in a full-scale passenger ferry conversion Stena Germanica in 2015 which is supported by European Union through the pilot Action part of TEN-T Priority Project 21. It should be noteworthy that the European Union has contributed 50% to total project cost. Apart from retrofitting the ship, the pilot Action supported port infrastructure establishment for the supply of Methanol for bunkering (European Commission, 2014).

3.2.3.2 Externalities

The shipping industry has exerted negative externalities in the form of air pollution to natural habitats and ecosystems (Ng & Song, 2010). In the process of social interaction, Buchanan & Stubblebine (1962) found "externalities may occur if some actors do not find it in their interest to take account of the consequences of their actions on others". Fundamentally, externalities indicate the divergence between private and social costs. This externalities are not mentioned in the cost functions of shipowners. Nonetheless, they refer to social cost (Han, 2010). An externality occurs when the economic or social activities of a group of people affect another group and this influence is not completely accountable, or reimbursed for, by the former group (European Commission, 2003). Consequently, externalities assessment is vital to a cost internalization policy and/or in cost-benefit analysis where the costs for measures establishment minimize impacts on environmental problem are compared with the benefits. Externalities study on shipping undertaken by Maffii et al. (2007) indicate that in 2006, the externalities of SO_x, NO_x and PM emissions from international shipping contributed to 183 billion euro. Regionally, Ballini (2013) calculated in his study that from May to August 2012, the total external health cost of emissions from cruise ships at berth in Copenhagen was more than 5 million euro. In this study, externalities arising from shipping operation mention their adverse effects on acidification (SO_x and NO_x), eutrophication (NO_x), climate impact (CO_2), and human health (SO_x, NO_x, CO_2 and PM).

Chapter 4. Methodology

After surveying the literature on criteria for assessment of technological alternatives in the last chapter, it can be concluded that there are inconsistencies in terms of the value of several criteria such as capital cost, operational cost, impact on NO_x reduction and impact on PM reduction with reference to alternatives given by different researches. Albeit some of criteria are in the form of numbers, they tend to be described as intervals instead of crisp numbers. By way of illustration, the figure of emissions reduction such as SO_x, NO_x, CO_2, and PM reduction are likely to be depicted in intervals format. In addition, the likelihood is that criteria regarding economic perspective are hard to be described quantitatively since capital cost and operational cost, for example, are not fixed values on the account of the variations in unpredictable market. Furthermore, in terms of social aspect, criteria such as government and industry support is unquantifiable. In order to overcome the deficiencies and vagueness in the criteria evaluation for selecting alternative technologies for emissions reduction from shipping, this study proposes an integrated fuzzy MCDM approach by the combination of two techniques namely fuzzy AHP and fuzzy TOPSIS.

This chapter discusses fuzzy set theory with some basic definitions of fuzzy numbers then the proposed MCDM method will be described in more detail.

4.1 Fuzzy set theory

Fuzzy set theory or fuzzy logic, firstly proposed by Zadeh (1965), could take uncertainty into account and address issues under uncertain and imprecise information. With the help of methodology of fuzzy set theory, users can compute with words directly. The fuzzy set theory is an effective tool for handling problem of vagueness and expressions of fuzziness which are more natural for human's perception than rigid mathematical equations (Vahdani and Hadipour, 2010). A fuzzy set is a general form of a crisp set. Fuzzy number sets are defined in the closed interval 0 and 1, where 1 expresses full membership and 0 describes non-membership. Meanwhile, crisp sets only allow 0 or 1. There are different kinds of fuzzy numbers such as trapezoidal fuzzy number or triangular fuzzy number that can be employed based on the condition. Triangular fuzzy numbers are normally utilized since they are simple to compute and useful in the process of handling information in a fuzzy environment.

According to Dubois & Prade (1978), Kaufmann & Gupta (1991) the concept fuzzy numbers can be defined as follows:

Definition 1: A real fuzzy number A is described as any fuzzy subset of the real line R with membership function f_A, which has the following properties:

f_A is a continuous mapping from R to the closed interval $[0, 1]$.

$f_A\ (x) = 0$, for all $x \in (-\infty, a]$.

fA is strictly increasing on $[a, b]$.

$f_A\ (x) = 1$, for all $x \in [b, c]$.

fA is strictly decreasing on $[c, d]$.

$f_A\ (x) = 0$, for all $x \in (d, \infty]$.

where a, b, c and d are real numbers. Unless elsewhere specified, assuming A is convex and bounded (i.e., $-\infty < a, d < \infty$).

Definition 2: The fuzzy number A = $[a,,c,d]$ is a trapezoidal fuzzy number if its membership function is given by:

$$f_A(x) = \begin{cases} f_A^L(x), & a \leq x \leq b \\ 1, & b \leq x \leq c \\ f_A^R(x), & c \leq x \leq d \\ 0, & otherwise \end{cases} \quad (1)$$

where $f_A^L(x)$ and $f_A^R(x)$ are the left and right membership functions of A, correspondingly (Kaufmann & Gupta, 1991).

When $b = c$, the trapezoidal fuzzy number is reduced to a triangular fuzzy number and can be denoted by $A = (a,\ b,\ d)$. Hence, triangular fuzzy numbers are special cases of trapezoidal fuzzy numbers.

Definition 3: The distance between fuzzy triangular numbers

Let $A = (a_1, b_1, d_1)$ and $B = (a_2, b_2, d_2)$ be two triangular fuzzy numbers. The distance between them is given using the vertex method by:

$$d(A,B) = \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (d_1 - d_2)^2]} \qquad (2)$$

Definition 4: α-cuts

The α-cuts of fuzzy number A can be defined as $A^{\alpha} = \{x \mid f_A(x) \geq \alpha)\}, \alpha \in [0,1]$ where A^{α} is a nonempty bounded closed interval contained in R and can be denoted by $A^{\alpha} = [A_l^{\alpha}, A_u^{\alpha}]$ where A_l^{α} and A_u^{α} are its lower and upper bounds, respectively (Kaufmann & Gupta, 1991). For example, if a triangular fuzzy number A = (a, b, d), then the α-cuts of A can be expressed as follows:

$$A^{\alpha} = [A_l^{\alpha}, A_u^{\alpha}] = [(b-a)\alpha + a, (b-d)\alpha + d] \qquad (3)$$

Definition 5: Arithmetic operations on fuzzy numbers

Given fuzzy numbers A and B where $A, B \in R^{+}$, the α-cuts of A and B are $A^{\alpha} = [A_l^{\alpha}, A_u^{\alpha}]$, $B^{\alpha} = [B_l^{\alpha}, B_u^{\alpha}]$, correspondingly.

The operations of A and B can be expressed by the interval arithmetic:

$$(A \oplus B)^{\alpha} = [A_l^{\alpha} + B_l^{\alpha}, A_u^{\alpha} + B_u^{\alpha}],$$

$$(A \ominus B)^{\alpha} = [A_l^{\alpha} - B_l^{\alpha}, A_u^{\alpha} - B_u^{\alpha}],$$

$$(A \otimes B)^{\alpha} = [A_l^{\alpha} \cdot B_l^{\alpha}, A_u^{\alpha} \cdot B_u^{\alpha}], \qquad (4)$$

$$(A \oslash B)^{\alpha} = \left[\frac{A_l^{\alpha}}{B_l^{\alpha}}, \frac{A_u^{\alpha}}{B_u^{\alpha}}\right],$$

$$(A \otimes r)^{\alpha} = [A_l^{\alpha} \cdot r, A_u^{\alpha} \cdot r], \qquad r \in R^{+}$$

4.2 The proposed integrated fuzzy MCDM approach

The proposed integrated fuzzy MCDM approach is demonstrated in figure 16. All stages of this proposed approach are discussed as follows.

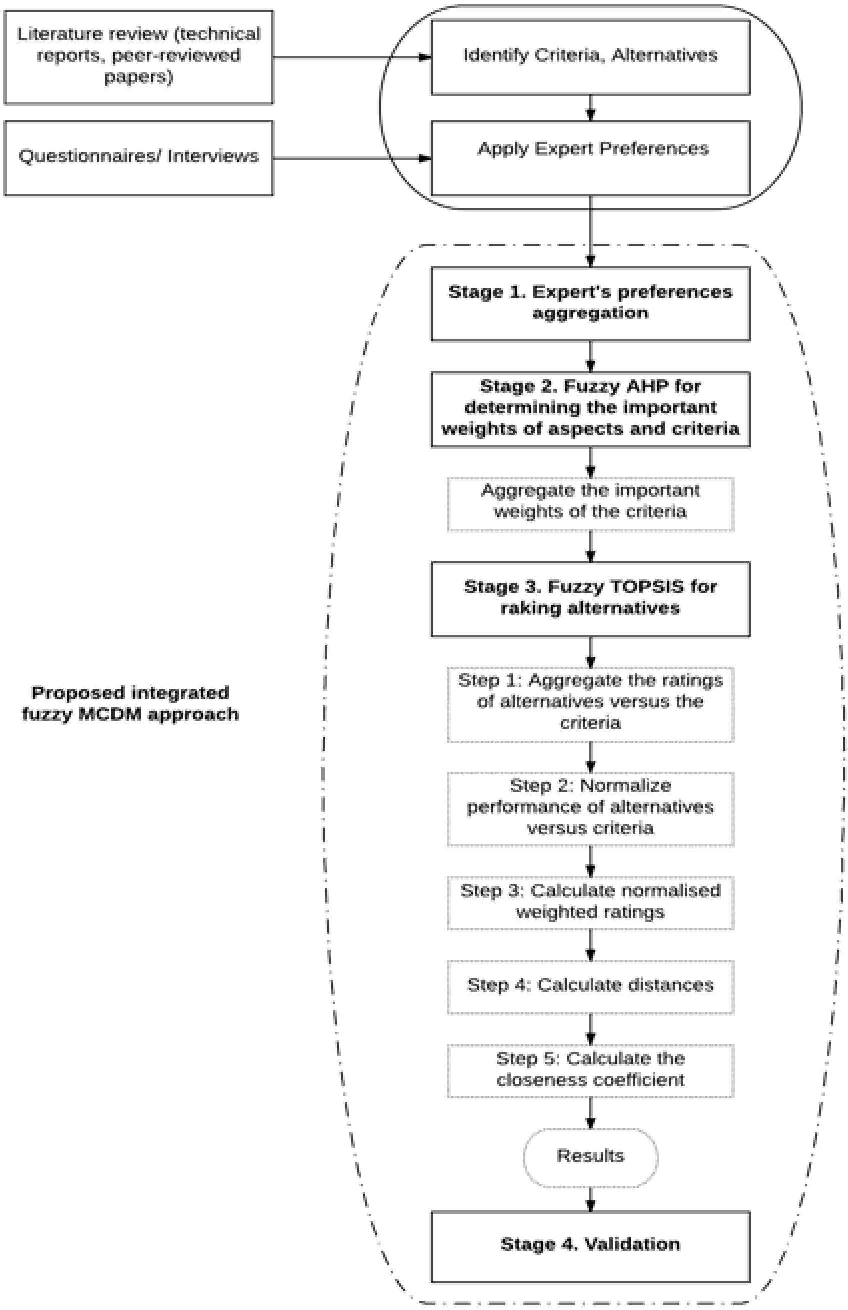


Figure 16. Schematic diagram of proposed method

4.2.1 Expert's preferences aggregation

With a view to aggregating the preferences in the important weights of aspects/ criteria assessed by a group of experts then building pairwise comparison matrix, the following methods are proposed based on arithmetic operations (Khazaeni et al., 2012).

Let $z_{ijt} = \left(a_{ijt}, b_{ijt}, c_{ijt}\right), i = 1, 2, \dots, m; j = 1, 2, \dots, n; t = 1, 2, \dots, l$ be the suitability important weight assigned to one aspect/ criterion over another aspect/ criterion by decision maker DM_t. The averaged suitability important weight $z_{ij} = \left(a_{ij}, b_{ij}, c_{ij}\right)$ can be calculated as follows:

$$z_{ij} = \left(a_{ij}, b_{ij}, c_{ij}\right) = \frac{1}{l} \otimes \left(a_{ij1} \oplus a_{ij2} \oplus \dots \oplus a_{ijt} \oplus \dots \oplus a_{ijl}\right) \qquad (5)$$

where

$$a_{ij} = \frac{1}{l} \sum_{t=1}^{l} a_{ijl}, \; b_{ij} = \frac{1}{l} \sum_{t=1}^{l} b_{ijl}, \; c_{ij} = \frac{1}{l} \sum_{t=1}^{l} g_{ijl}.$$

4.2.2 Fuzzy AHP in determining the important weights of the aspects and criteria

In order to determine the important weights of the criteria, fuzzy AHP approach is applied by using triangular fuzzy number to express experts' judgments given as interval for their preferences of one aspect or criterion over another. Weight vectors of aspect or criteria then are determined by calculating the synthetic extent value of the pairwise comparison. This approach is derived from the extent analysis methodology proposed by Chang (1996) which is popular and simple in computation. Chang's fuzzy AHP approach is discussed as follows:

4.2.2.1 Fuzzy synthetic extent calculation

Let $X = \{x_1, x_2, x_3, \dots, x_n\}$ be an object set, and $U = \{u_1, u_2, u_3, \dots, u_n\}$ be a goal set. Each object is taken and an extent analysis for each goal g_i is performed respectively (Chang, 1996). Thus, the m extent analysis values for each object can be calculated, and are denoted as follows:

$M_{gi}^{1}, M_{gi}^{2}, \dots, M_{gi}^{m} \quad i = 1, 2, \dots, n$

where all the M_{gi}^{j} $(j = 1,2, \ldots, m)$ are triangular fuzzy numbers.

With respect to the jth object for m goals, the value of fuzzy synthetic extent is defined as:

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{gi}^{j} \right]^{-1} \qquad (6)$$

where $\sum_{j=1}^{m} M_{gi}^{j} = \left(\sum_{j=1}^{m} l_j , \sum_{j=1}^{m} m_j , \sum_{j=1}^{m} u_j \right), (j = 1, 2, \ldots, m),\ (i = 1, 2, \ldots, n)$

4.2.2.2 Comparison of fuzzy values

The degree of possibility of two triangular fuzzy numbers $M_1 = (l_1, m_1, u_1) \geq M_2 = (l_2, m_2, u_2)$ is defined as follows:

$$V(M_1 \geq M_2) = \underbrace{SUP}_{x \geq y} \left[\min \left(\mu_{M_1}(x), \mu_{M_2}(y) \right) \right] \qquad (7)$$

when a pair (x, y) exists such that $x \geq y$ and $\mu_{M_1}(x) = \mu_{M_2}(y) = 1$ then we have $V(M_2 \geq M_1)$. Because M_1 and M_2 are convex fuzzy numbers, the membership degree of possibility is identified as follows:

$$V(M_1 \geq M_2) = hgt\ (M_1 \cap M_2) = \mu_{M_2}(d) \qquad (8)$$

where d is the ordinate of the highest intersection point D between μ_{M_1} and μ_{M_2}, as shown in Figure 17. When $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$, then $\mu_{M_2}(d)$ is given as follows:

$$\mu_{M_2}(d) = \begin{cases} 1, & if\ m_1 \geq m_2 \\ 0, & if\ l_2 \geq u_1 \\ \dfrac{(l_2 - u_1)}{(l_2 - u_1) + (m_1 - m_2)}, & otherwise \end{cases} \qquad (9)$$

To compare M_1 and M_2 we need both the values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$

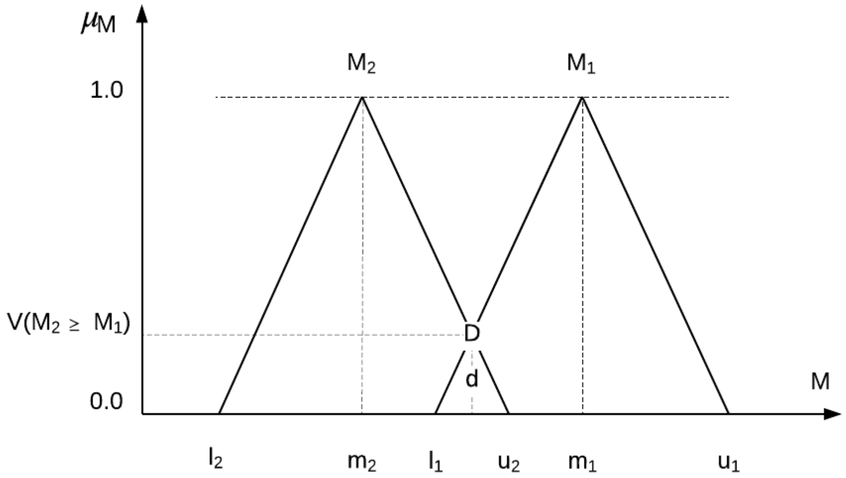


Figure 17. Intersection between M_1 and M_2

4.2.2.3 Priority weight calculation

The degree possibility of convex fuzzy number to be greater than k convex fuzzy numbers M_i $(i = 1, 2, \dots k)$ can be expressed as follows:

$$V(M \geq M_1, M_2, \dots, M_k) = V[(M \geq M_1) \; and \; (M \geq M_2) \; and \dots \; (M \geq M_k)] \quad (10)$$

$$V(M \geq M_1, M_2, \dots, M_k) = \min V(M \geq M_i) \;\; i = 1, 2, \dots, k \quad (11)$$

If

$$d'(A_i) = \min V(S_i \geq S_k) \; k = 1, 2, \dots, n; k \neq i \quad (12)$$

Then the weight vector is given by

$$W'(A_i) = \left(d'(A_1), d'(A_2), \dots d'(A_n)\right)^T \quad (13)$$

Here A_i $(i = 1, 2, \dots, n)$ are n elements

4.2.2.4 Calculation of normalized weight vector

Via normalization of $W'(A_i)$

$$d\,(A_i) = \frac{d'(A_i)}{\sum_{i=1}^{n} d'(A_i)} \quad (14)$$

Then the normalized weight vectors are obtained as follows:

$$W\,(A_i) = \left(d\,(A_1), d\,(A_2), \dots d\,(A_n)\right)^T \quad (15)$$

Where W is a non-fuzzy number.

4.3 Fuzzy TOPSIS in ranking alternatives

According to Chen (2016), the fuzzy TOPSIS procedure is discussed as follows:

4.3.1 Aggregate the ratings of alternatives versus criteria

Let $x_{ijt} = (e_{ijt}, f_{ijt}, g_{ijt}), i = 1, 2, \dots, m; j = 1, 2, \dots, n; t = 1, 2, \dots, k$ be the suitability rating assigned to alternative A_i, by decision maker DM_t, for criterion C_i. The averaged suitability rating $x_{ij} = (e_{ij}, f_{ij}, g_{ij})$ can be calculated as follows:

$$x_{ij} = (e_{ij}, f_{ij}, g_{ij}) = \frac{1}{k} \otimes (x_{ij1} \oplus x_{ij2} \oplus \dots \oplus x_{ijt} \oplus \dots \oplus x_{ijk}) \qquad (16)$$

where

$$e_{ij} = \frac{1}{k}\sum_{t=1}^{k} e_{ijk}, f_{ij} = \frac{1}{k}\sum_{t=1}^{k} f_{ijk}, g_{ij} = \frac{1}{k}\sum_{t=1}^{k} g_{ijk}.$$

4.3.2 Normalize performance of alternatives versus criteria

In order to ensure compatibility between average ratings and average weightings, the average ratings are normalized into comparable scales. Assume that $r_{ij} = (a_{ij}, b_{ij}, c_{ij})$ is the performance of alternative i on criteria j. Then the normalized value can be denoted as follows:

$$\begin{aligned} x_{ij} &= \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), \quad j \in B \\ & \qquad\qquad\qquad\qquad\qquad (17) \\ x_{ij} &= \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), \quad j \in C \end{aligned}$$

where $a_j^- = min_i a_{ij}, c_j^* = max_i c_{ij}, i = 1, \dots, m; j = 1, \dots, n.$ B is for benefit criterion whereas C is for cost criterion.

4.3.3 Calculate normalized weighted rating

The normalized weighted ratings G_i can be computed by multiplying the importance weights of criteria w_j with the values of the normalized average rating x_{ij} as follows:

$$G_i = x_{ij} \otimes w_j, i = 1, \dots, m; j = 1, \dots, n. \tag{18}$$

4.3.4 Calculate distances

The fuzzy positive ideal solution (FPIS) A^+ and fuzzy negative ideal solution (FNIS) A^- can be obtained as follows:

$$\begin{aligned} A^+ &= (1.0, 1.0, 1.0) \\ A^- &= (0.0, 0.0, 0.0) \end{aligned} \tag{19}$$

The distance of each alternative $A_i, i = 1, \dots, m$ from the FPIS A^+ and NPIS A^- is calculated as follows:

$$\begin{aligned} d_i^+ &= \sqrt{\sum_{i=1}^{m} (G_i - A^+)^2} \\ d_i^- &= \sqrt{\sum_{i=1}^{m} (G_i - A^-)^2} \end{aligned} \tag{20}$$

where d_i^+ accounts for the shortest distance of alternative A_i and d_i^- accounts for the furthest distance of alternative A_i.

4.3.5 Calculate the closeness coefficient

The closeness coefficient of each alternative is obtained as follows:

$$CC_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{21}$$

A higher value of the closeness coefficient shows that an alternative is closer to FPIS and further from FNIS at the same time. The closeness coefficient of each alternative is defined to determine the prioritization of all alternatives from the best to the worst among a set of finite feasible alternatives.

4.4. Validation

One of the most useful tool to validate the robustness of the results is sensitivity analysis where the changes in the priority weights of criteria are conducted and the behaviors of alternatives are analyzed whether they changed accordingly (Mokhtari et al., 2012). The concept of this technique is to change the priority weights obtained from the fuzzy AHP technique mutually (Önüt & Soner, 2008). A number of experiments depend on the number of criteria and each experiment will generate a new scenario with the aim of determining which criterion has the most significant influence upon the decision-making process (Yazdani-Chamzini & Yakhchali, 2012). The base scenario is the original outputs of the case study. The CC_i that indicate the prioritization of alternatives will be computed for each alternative in each scenario, and will be plotted to illustrate the changes in these values with respect to the changes in the weights of criteria.

Chapter 5. Case study example

In order to illustrate the applicability of the proposed framework, four alternative technologies for regulatory compliance towards reducing emissions from ships including Low sulphur fuels (A_1), HFO with scrubbers (A_2), LNG (A_3) and Methanol (A_4) were analyzed. Nine criteria discussed in detail in previous chapter are specified as follows:

Table 8. The criteria for assessing technological alternatives

Aspect	Code	Criteria	Code	Type
Economic	EC	Capital cost (CAPEX)	C_1	Cost
		Operational cost (OPEX)	C_2	Cost
		Life-cycle cost	C_3	Cost
Environmental	EN	Impact on SO_x reduction	C_4	Benefit
		Impact on NO_x reduction	C_5	Benefit
		Impact on GHG reduction	C_6	Benefit

		Impact on PM reduction	C_7	Benefit
Social	SO	Government and industry support	C_8	Benefit
		Externalities	C_9	Cost

Criteria can be divided into two types. The first type is Cost which means the larger, the less preference. The second type is Benefit which means the larger, the more preference (Shih et al., 2007).

In this study, the data used as input for implementing the proposed framework were collected by undertaking interviews with officials of Stena Lines in Gothenburg. The semi-structured interviews were conducted with Mr. Per Stefensson who is Marine Standard Advisor, Mr. Erik Lewenhaupt who is Head of Sustainability and Ms. Cecilia Andersson who is Environment Manger of Sustainability Department. They were asked to evaluate respectively the important weights of selected aspects and criteria then ratings alternatives based on their preferences. With the purpose of deciding the different important weights of each aspect, criterion, each interviewee was asked to make pairwise comparison in respect of different aspect, criterion using fuzzy linguistic assessment variables (Chen et al., 2016) which is a “Likert scale” of fuzzy number starting from 1 to 9 in order to transform of linguistic data into triangular fuzzy numbers as illustrated in table 9.

Table 9. Linguistic terms and the corresponding triangular fuzzy numbers for determining important weight of aspect and criteria

Linguistic terms for importance	Code	Triangular fuzzy numbers $\boldsymbol{M} = (\boldsymbol{l}, \boldsymbol{m}, \boldsymbol{u})$
Just equal	JE	$(1.0, 1.0, 1.0)$
Equal importance	EQI	$(1.0, 1.0, 3.0)$

Weak importance	WI	$(1.0, 3.0, 5.0)$
Strong importance	SI	$(3.0, 5.0, 7.0)$
Very strong importance	VSI	$(5.0, 7.0, 9.0)$
Extremely importance	EXI	$(7.0, 9.0, 9.0)$
Reciprocals		The reciprocals of above fuzzy numbers $M_1^{-1} \sim (1/u_1, 1/m_1, 1/l_1)$

In the table 9, the reciprocals mean if factor i has one of above numbers assigned to it when compared to factor j, then j has the reciprocal value when compared to i.

5.1. Expert's preferences aggregation

The decision makers were asked to assign the important weight of one aspect over another aspect (by pairwise comparison). The results of the preferences of three decision makers towards aspects are reported as shown in table 10. The data after that have been transformed into triangular fuzzy number as shown in table 11.

Table 10. Preferences of decision makers towards aspects

Aspect	Decision makers	EC	EN	SO
EC	DM_1	JE	VSI	VSI
	DM_2	JE	SI	EQI
	DM_3	JE	SI	VSI
EN	DM_1		JE	EQI
	DM_2		JE	SI

	DM_3		JE	SI
SO	DM_1			JE
	DM_2			JE
	DM_3			JE

Table 11. Transforming the preferences of decision makers towards aspects into fuzzy triangular numbers

Aspect	Decision makers	EC	EN	SO
EC	DM_1	$(1.0, 1.0, 1.0)$	$(5.0, 7.0, 9.0)$	$(5.0, 7.0, 9.0)$
	DM_2	$(1.0, 1.0, 1.0)$	$(3.0, 5.0, 7.0)$	$(1.0, 1.0, 3.0)$
	DM_3	$(1.0, 1.0, 1.0)$	$(3.0, 5.0, 7.0)$	$(5.0, 7.0, 9.0)$
EN	DM_1		$(1.0, 1.0, 1.0)$	$(1.0, 1.0, 3.0)$
	DM_2		$(1.0, 1.0, 1.0)$	$(3.0, 5.0, 7.0)$
	DM_3		$(1.0, 1.0, 1.0)$	$(3.0, 5.0, 7.0)$
SO	DM_1			$(1.0, 1.0, 1.0)$
	DM_2			$(1.0, 1.0, 1.0)$
	DM_3			$(1.0, 1.0, 1.0)$

The aggregation of experts' preferences are performed with the help of Eq. (5). For illustrative purpose, the aggregated fuzzy comparison matrix for determining the priority weights of three aspects including economic, environmental and social are obtained as shown in table 12.

Table 12. Aggregated fuzzy comparison matrix of aspect

Aspects	EC	EN	SO
EC	$(1.00, 1.00, 1.00)$	$(3.67, 5.67, 7.67)$	$(3.67, 5.00, 7.00)$
EN	$(0.13, 0.18, 0.27)$	$(1.00, 1.00, 1.00)$	$(2.33, 3.67, 5.67)$
SO	$(0.14, 0.20, 0.27)$	$(0.18, 0.27, 0.43)$	$(1.00, 1.00, 1.00)$

5.2 Application of fuzzy AHP in determining priority weights of aspect

5.2.1 Fuzzy synthetic extent calculation

The values of fuzzy synthetic extent of three aspects with regard to the goal are calculated as below by applying Eq. (6).

$$S_1 = S_{EC} = (8.3333, 11.6667, 15.6667) \otimes \left(\frac{1}{24.3074}, \frac{1}{17.9825}, \frac{1}{13.1164}\right)^{-1}$$
$$= (0.3428, 0.6488, 1.1944)$$

$$S_2 = S_{EN} = (3.4638, 4.8431, 6.9394) \otimes \left(\frac{1}{24.3074}, \frac{1}{17.9825}, \frac{1}{13.1164}\right)^{-1}$$
$$= (0.1425, 0.2693, 0.5291)$$

$$S_3 = S_{SO} = (1.3193, 1.4727, 1.7013) \otimes \left(\frac{1}{24.3074}, \frac{1}{17.9825}, \frac{1}{13.1164}\right)^{-1}$$
$$= (0.0543, 0.0819, 0.1297)$$

5.2.2 Comparison of fuzzy values

Using Eq. (8), (9) to calculate the V values. The degree of possibility of $S_{EN} \geq S_{EC}$ can be calculated as

$$V(S_{EN} \geq S_{EC}) = \frac{0.3428 - 0.5291}{(0.3428 - 0.5291) + (0.2693 - 0.6488)} = 0.3292$$

Similarly, other V values can be calculated as shown in table 13.

Table 13. V values for aspects

Aspects	EC	EN	SO
EC	/	1	1
EN	0.3292	/	1
SO	0	0	/

5.2.3 Priority weight calculation

By using Eq. (12), the minimum degree of possibility can be obtained as follows

$$d'(EN\ ) = \min V(S_{EN} \geq S_{EC}, S_{SO}) = \min(0.3292, 1) = 0.3292$$

Similarly, $d'_{Ec} = 1.0000$; $d'_{SO} = 0.0000$.

Then the weight vector is given with the help of Eq. (13)

$$W' = \left(d'(EC\ ), d'(EN\ ), d'(SO\ )\right)^T = \ (1.0000, 0.3292, 0.0000)^T$$

5.2.4 Calculation of normalized weight vector

Finally, after normalization of W' by applying Eq. (14) and (15), the normalized weight vectors are determined as follows:

$$W\ (A_i\ ) = (0.7523, 0.2477, 0.0000)^T$$

Therefore, the calculated weights of three aspects including economic, environmental and social are $0.7523, 0.2477, 0.0000$ respectively.

Table 14. Weights of economic, environmental and social aspect

Aspects	Fuzzy weight	Normalized weight
EC	$(0.3428, 0.6488, 1.1944)$	0.7523
EN	$(0.1425, 0.2693, 0.5291)$	0.2477
SO	$(0.0543, 0.0819, 0.1297)$	0.0000

It can be clearly seen from table 14 that economic aspect is of paramount importance since the input data generated from the outcomes of interviews with a group of experts who are ship operators. It is reasonable because profitability is the most concern to shipowners and operators. It is compulsory that the technological alternatives meet the current environmental requirements (SO_x and NO_x regulations). However, the environmental regulations are forecasted to be stricter in the near future. Therefore, the environmental aspect comprising the impacts of SO_x, NO_x, GHG and PM reduction is the second important consideration when selecting alternatives for cleaner shipping. At the bottom end is social aspect, even though all the clean technologies for shipping are increasingly supported by the public and the authorities.

Afterwards, the weights of criteria in each aspect (economic, environmental and social) are determined. The calculations are not given here since they follow the same procedure as discussed above.

For the sake of deciding the important priority weights of three criteria in economic aspect including Capital cost (CAPEX, C_1), Operational cost (OPEX, C_2) and Life-cycle cost (C_3), the aggregated fuzzy comparison matrix is established as demonstrated in table 16 based on the preferences of decision makers towards economic criteria as shown in the table 15. The weights of C_1, C_2 and C_3 are presented in table 17.

Table 15. Preferences of decision makers towards economic criteria

Criterion	Decision makers	C_1	C_2	C_3
C_1	DM_1	JE	EQI	SI
	DM_2	JE	VSI	SI
	DM_3	JE	SI	VSI
C_2	DM_1		JE	VSI
	DM_2		JE	EQI
	DM_3		JE	WI
C_3	DM_1			JE
	DM_2			JE
	DM_3			JE

Table 16. Aggregated fuzzy comparison matrix of criteria in economic aspect

Criteria	C_1	C_2	C_3
C_1	$(1.00, 1.00, 1.00)$	$(3.00, 4.33, 6.33)$	$(3.67, 5.67, 7.67)$
C_2	$(0.16, 0.23, 0.33)$	$(1.00, 1.00, 1.00)$	$(2.33, 3.67, 5.67)$
C_3	$(0.13, 0.18, 0.27)$	$(0.18, 0.27, 0.43)$	$(1.00, 1.00, 1.00)$

Table 17. Weights of criteria in economic aspect

Criteria	Fuzzy weight	Normalized weight
C_1	$(0.3235, 0.6341, 1.2034)$	0.7124
C_2	$(0.1473, 0.2823, 0.5616)$	0.2876
C_3	$(0.0551, 0.0835, 0.1365)$	0.0000

Similarly, the important weights of four criteria in environmental aspect including Impact on SO_x reduction (C_4), Impact on NO_x reduction (C_5), Impact on GHG reduction (C_6) and Impact on PM reduction (C_7) are determined as shown in table 20 based on the outputs from table 18 and table 19.

Table 18. Preferences of decision makers towards environmental criteria

Criterion	Decision makers	C_4	C_5	C_6	C_7
C_4	DM_1	JE	VSI	EXI	VSI
	DM_2	JE	EXI	EQI	EXI
	DM_3	JE	SI	EQI	SI
C_5	DM_1		JE	VSI	EQI
	DM_2		JE	WI	VSI
	DM_3		JE	SI	EQI
C_6	DM_1			JE	WI
	DM_2			JE	VSI
	DM_3			JE	SI
C_7	DM_1				JE

DM_2	JE
DM_3	JE

Table 19. Aggregated fuzzy comparison matrix of criteria in environmental aspect

Criteria	C_4	C_5	C_6	C_7
C_4	$(1.00, 1.00, 1.00)$	$(5.00, 7.00, 8.33)$	$(3.00, 3.67, 5.00)$	$(5.00, 7.00, 8.33)$
C_5	$(0.12, 0.14, 0.20)$	$(1.00, 1.00, 1.00)$	$(3.00, 5.00, 7.00)$	$(2.33, 3.00, 5.00)$
C_6	$(0.20, 0.27, 0.33)$	$(0.14, 0.20, 0.33)$	$(1.00, 1.00, 1.00)$	$(3.00, 5.00, 7.00)$
C_7	$(0.12, 0.14, 0.20)$	$(0.20, 0.33, 0.43)$	$(0.14, 0.20, 0.33)$	$(1.00, 1.00, 1.00)$

Table 20. Weights of criteria in environmental aspect

Criteria	Fuzzy weight	Normalized weight
C_4	$(0.3011, 0.5191, 0.8632)$	0.6619
C_5	$(0.1388, 0.2543, 0.5027)$	0.2861
C_6	$(0.0934, 0.1800, 0.3300)$	0.0520
C_7	$(0.0315, 0.0466, 0.0747)$	0.0000

Calculating the same way, the important weights of two criteria in social aspect namely Government and industry support (C_8) and Externalities (C_9) are obtained as shown in table 23 based on the outputs from table 21 and 22.

Table 21. Preferences of decision makers towards social criteria

Criterion	Decision makers	C_8	C_9
C_8	DM_1	JE	SI
	DM_2	JE	JE
	DM_3	JE	EQI
C_9	DM_1		JE
	DM_2		JE
	DM_3		JE

Table 22. Aggregated fuzzy comparison matrix of criteria in social aspect

Criteria	C_8	C_9
C_8	$(1.00, 1.00, 1.00)$	$(1.67, 2.33, 3.67)$
C_9	$(0.27, 0.43, 0.60)$	$(1.00, 1.00, 1.00)$

Table 23. Weights of criteria in social aspect

Criteria	Fuzzy weight	Normalized weight
C_8	$(0.4255, 0.7000, 1.1846)$	1.0000
C_9	$(0.2031, 0.3000, 0.4062)$	0.0000

Now, the global fuzzy weights of the criteria with regard to the goal can be obtained. Taking the Capital cost (C_1) as example, the global fuzzy weight of C_1 = the fuzzy weight of C_1 in the economic aspect $\otimes$ the normalized weight of economic aspect $= (0.3235, 0.6341, 1.2034) \otimes\ 0.7523 = (0.2434, 0.4771, 0.9053)$. By doing the same pattern, the global fuzzy weights of other criteria can be determined as given in table 24.

Table 24. Global fuzzy weight of criteria

Criteria	Global fuzzy weight
C_1	$(0.2434, 0.4771, 0.9053)$
C_2	$(0.1108, 0.2124, 0.4225)$
C_3	$(0.0415, 0.0629, 0.1027)$
C_4	$(0.0746, 0.1286, 0.2138)$
C_5	$(0.0344, 0.0630, 0.1245)$
C_6	$(0.0231, 0.0446, 0.0817)$
C_7	$(0.0078, 0.0115, 0.0185)$
C_8	$(0.0000, 0.0000, 0.0000)$
C_9	$(0.0000, 0.0000, 0.0000)$

The feature as can be seen from the results is that the Social aspect is given a zero weight, resulting in global fuzzy weights of criteria C_8 and C_9 are also given zero weights. Wang et al. (2008) re-examined the fuzzy AHP with numerical examples and found that the extent analysis method may assign an irrational zero weight to some useful decision criteria, thus they are not considered in decision analysis. Given the input data for the fuzzy AHP mainly rely on experts' preferences, Social aspect is not evinced interest from shipowners compared to economic and environmental aspect. Therefore, the criterion C_8 and C_9 are then not to be considered in the following evaluation procedure.

5.3. Application of fuzzy TOPSIS in ranking alternatives

5.3.1. Aggregate the ratings of alternatives versus criteria

The discussion has been further proceeded to determine the performance of alternatives with respect to the criteria. Decision makers were required to rate each alternative according to each criterion by using the linguistic terms as show in table 25 (Chen et al., 2016).

Table 25. Linguistic terms and the corresponding triangular fuzzy numbers for rating for alternatives with respect to criteria.

Linguistic variables	Code	Triangular fuzzy numbers
Very poor	VP	$(0.0, 0.1, 0.2)$
Poor	P	$(0.1, 0.3, 0.5)$
Fair	F	$(0.3, 0.5, 0.7)$
Good	G	$(0.5, 0.7, 0.9)$
Very good	VG	$(0.8, 0.9, 1.0)$

The input of experts along with aggregated suitability ratings of four alternatives by using Eq. (16) are given in table 26.

Table 26. Aggregation of alternatives ratings versus criteria

Criteria	Alternatives	Decision makers			$\boldsymbol{r_{ij}}$
		DM$_1$	DM$_2$	DM$_3$	
C$_1$	A$_1$	VG	G	VG	$(0.700, 0.833, 0.967)$
	A$_2$	F	P	F	$(0.233, 0.433, 0.633)$
	A$_3$	VP	VP	P	$(0.033, 0.167, 0.300)$
	A$_4$	F	F	F	$(0.300, 0.500, 0.700)$

C_2	A_1	P	G	P	(0.233, 0.433, 0.633)
	A_2	G	VG	G	(0.600, 0.767, 0.933)
	A_3	P	G	G	(0.367, 0.567, 0.767)
	A_4	P	G	P	(0.233, 0.433, 0.633)
C_3	A_1	G	P	F	(0.300, 0.500, 0.700)
	A_2	F	F	G	(0.367, 0.567, 0.767)
	A_3	P	P	P	(0.100, 0.300, 0.500)
	A_4	F	F	P	(0.233, 0.433, 0.633)
C_4	A_1	G	G	F	(0.433, 0.633, 0.833)
	A_2	G	G	F	(0.433, 0.633, 0.833)
	A_3	VG	VG	VG	(0.800, 0.900, 1.000)
	A_4	VG	VG	VG	(0.800, 0.900, 1.000)
C_5	A_1	VP	P	P	(0.067, 0.233, 0.400)
	A_2	VP	P	P	(0.067, 0.233, 0.400)
	A_3	F	G	G	(0.433, 0.633, 0.833)
	A_4	F	G	G	(0.433, 0.633, 0.833)
C_6	A_1	VP	P	P	(0.067, 0.233, 0.400)
	A_2	VP	P	P	(0.067, 0.233, 0.400)
	A_3	P	F	G	(0.300, 0.500, 0.700)

	A_4	F	P	P	$(0.167, 0.367, 0.567)$
C_7	A_1	F	F	F	$(0.300, 0.500, 0.700)$
	A_2	F	F	G	$(0.367, 0.567, 0.767)$
	A_3	VG	G	VG	$(0.700, 0.833, 0.967)$
	A_4	VG	VG	VG	$(0.800, 0.900, 1.000)$
C_8	A_1	G	G	G	$(0.500, 0.700, 0.900)$
	A_2	G	F	F	$(0.367, 0.567, 0.767)$
	A_3	VG	VG	VG	$(0.800, 0.900, 1.000)$
	A_4	VG	G	VG	$(0.700, 0.833, 0.967)$
C_9	A_1	G	G	G	$(0.500, 0.700, 0.900)$
	A_2	F	F	F	$(0.300, 0.500, 0.700)$
	A_3	VG	VG	VG	$(0.800, 0.900, 1.000)$
	A_4	G	G	VG	$(0.600, 0.767, 0.933)$

As discussed before, criteria C_8 and C_9 are no longer taken into consideration in the decision analysis and thus they are not included in the calculation process.

5.3.2 Normalize performance of alternatives versus criteria

It is unnecessary to normalize the averaged ratings of alternatives with respect to criteria into comparable values compatible with the weights of criteria since all the fuzzy numbers of performance values are in the range of $[0,1]$.

5.3.3 Calculate normalized weighted rating

The normalized weighted ratings G_i can be calculated with the help of Eq. (18) as demonstrated in table 27.

Table 27. Normalized weighted ratings of each alternatives

Alternatives	Normalized weighted ratings $\boldsymbol{G_i}$
A_1	$(0.0353, 0.0905, 0.2126)$
A_2	$(0.0254, 0.0740, 0.1888)$
A_3	$(0.0200, 0.0580, 0.1485)$
A_4	$(0.0276, 0.0772, 0.1927)$

5.3.4 Calculate distances

The distance of each alternative from the FPIS A^+ and NPIS A^- can be determined by applying Eq. (19), (20) as illustrated in table 28.

Table 28. The distance of each alternative from the FPIS A^+ and NPIS A^-

Alternatives	$\boldsymbol{d^+}$	$\boldsymbol{d^-}$
A_1	1.5420	0.2337
A_2	1.5702	0.2043
A_3	1.6040	0.1607
A_4	1.5649	0.2094

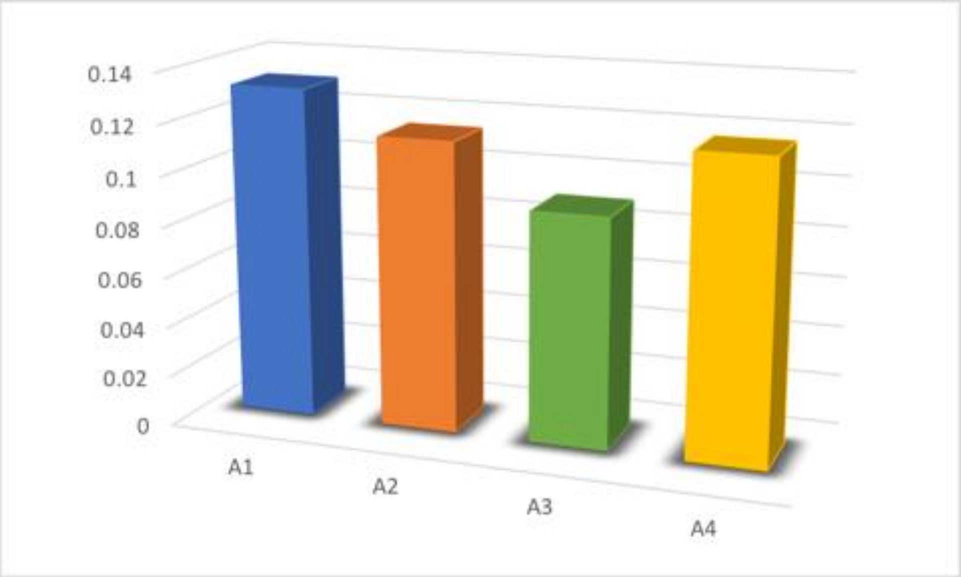
5.3.5: Calculate the closeness coefficient

The closeness coefficient of alternatives can be obtained by using Eq. (21) as shown in table 29 and figure 18.

Table 29. The closeness coefficient of alternatives CC_i

Alternatives	Closeness coefficient $\boldsymbol{CC_i}$	Ranking
A_1	0.1316	1
A_2	0.1151	3
A_3	0.0911	4
A_4	0.1180	2

Figure 18. The ranking of alternatives according to CC_i values



Therefore, based on the closeness coefficient CC_i values, the ranking of alternatives in descending order is $A_1 > A_4 > A_2 > A_3$.

5.4 Validation

In this study, sensitivity analysis was performed to elaborate the impact of changing priority weights of criteria on the ranking of alternatives. In order words, the implementation of sensitivity analysis aimed to see how sensitive the alternatives change with the priority weights of criteria. As mentioned in the previous stage, the criterion C_8 and C_9 are not so important and are eliminated from the decision analysis. For this reason, 21 scenarios will be generated by exchanging the weight of each criterion with another criterion weight. This work is associated with the calculation of CC_i values for each alternative in each scenario. Table 30 and figure 19 reveal graphically the results of sensitivity analysis.

Table 30. The sensitivity analysis results

Scenario	Global fuzzy weights of criteria	$\boldsymbol{CC_i}$ value	Relative ranking of alternatives
Original	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1316$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.1151$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.0911$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1180$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
1	$C_1 = (0.1108, 0.2124, 0.4225)$	$A_1 = 0.1160$	$A_2 > A_1 > A_4 > A_3$
	$C_2 = (0.2434, 0.4771, 0.9053)$	$A_2 = 0.1289$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.1111$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1150$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
2	$C_1 = (0.0415, 0.0629, 0.1027)$	$A_1 = 0.1109$	$A_2 > A_4 > A_1 > A_3$

	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.1248$	
	$C_3 = (0.2434, 0.4771, 0.9053)$	$A_3 = 0.1044$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1132$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
3	$C_1 = (0.0746, 0.1286, 0.2138)$	$A_1 = 0.1222$	$A_4 > A_3 > A_2 > A_1$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.1276$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.1354$	
	$C_4 = (0.2434, 0.4771, 0.9053)$	$A_4 = 0.1384$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
4	$C_1 = (0.0344, 0.0630, 0.1245)$	$A_1 = 0.0905$	$A_3 > A_4 > A_2 > A_1$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.0991$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.1279$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1275$	
	$C_5 = (0.2434, 0.4771, 0.9053)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		

	$C_7 = (0.0078, 0.0115, 0.0185)$		
5	$C_1 = (0.0231, 0.0446, 0.0817)$	$A_1 = 0.0884$	$A_3 > A_4 > A_2 > A_1$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.0983$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.1198$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1080$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.2434, 0.4771, 0.9053)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
6	$C_1 = (0.0078, 0.0115, 0.0185)$	$A_1 = 0.1086$	$A_3 > A_4 > A_2 > A_1$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.1259$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.1451$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1446$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.2434, 0.4771, 0.9053)$		
7	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1335$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.0415, 0.0629, 0.1027)$	$A_2 = 0.1102$	
	$C_3 = (0.1108, 0.2124, 0.4225)$	$A_3 = 0.0834$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1180$	

	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
8	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1352$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.0746, 0.1286, 0.2138)$	$A_2 = 0.1132$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.0956$	
	$C_4 = (0.1108, 0.2124, 0.4225)$	$A_4 = 0.1249$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
9	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1256$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.0344, 0.0630, 0.1245)$	$A_2 = 0.1008$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.0929$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1234$	
	$C_5 = (0.1108, 0.2124, 0.4225)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
10	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1248$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.0231, 0.0446, 0.0817)$	$A_2 = 0.0988$	

	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.0890$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1160$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.1108, 0.2124, 0.4225)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
11	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1340$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.0078, 0.0115, 0.0185)$	$A_2 = 0.1088$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.0990$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1323$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.1108, 0.2124, 0.4225)$		
12	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1302$	$A_1 > A_2 > A_4 > A_3$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.1145$	
	$C_3 = (0.0746, 0.1286, 0.2138)$	$A_3 = 0.0855$	
	$C_4 = (0.0415, 0.0629, 0.1027)$	$A_4 = 0.1139$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		

13	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1320$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.1157$	
	$C_3 = (0.0344, 0.0630, 0.1245)$	$A_3 = 0.0906$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1177$	
	$C_5 = (0.0415, 0.0629, 0.1027)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
14	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1310$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.1143$	
	$C_3 = (0.0231, 0.0446, 0.0817)$	$A_3 = 0.0915$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1179$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.0415, 0.0629, 0.1027)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
15	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1316$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.1151$	
	$C_3 = (0.0078, 0.0115, 0.0185)$	$A_3 = 0.0950$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1212$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		

	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0415, 0.0629, 0.1027)$		
16	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1278$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.1114$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.0893$	
	$C_4 = (0.0344, 0.0630, 0.1245)$	$A_4 = 0.1162$	
	$C_5 = (0.0746, 0.1286, 0.2138)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
17	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.2535$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.2255$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.1819$	
	$C_4 = (0.0231, 0.0446, 0.0817)$	$A_4 = 0.2299$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.0746, 0.1286, 0.2138)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
18	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1292$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.1139$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.0903$	

	$C_4 = (0.0078, 0.0115, 0.0185)$	$A_4 = 0.1180$	
	$C_5 = (0.0344, 0.0630, 0.1245)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0746, 0.1286, 0.2138)$		
19	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1316$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.1151$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.0905$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1170$	
	$C_5 = (0.0231, 0.0446, 0.0817)$		
	$C_6 = (0.0344, 0.0630, 0.1245)$		
	$C_7 = (0.0078, 0.0115, 0.0185)$		
20	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1344$	$A_1 > A_4 > A_2 > A_3$
	$C_2 = (0.1108, 0.2124, 0.4225)$	$A_2 = 0.1185$	
	$C_3 = (0.0415, 0.0629, 0.1027)$	$A_3 = 0.0925$	
	$C_4 = (0.0746, 0.1286, 0.2138)$	$A_4 = 0.1198$	
	$C_5 = (0.0078, 0.0115, 0.0185)$		
	$C_6 = (0.0231, 0.0446, 0.0817)$		
	$C_7 = (0.0344, 0.0630, 0.1245)$		
21	$C_1 = (0.2434, 0.4771, 0.9053)$	$A_1 = 0.1043$	$A_1 > A_4 > A_2 > A_3$

$C_2 = (0.1108, 0.2124, 0.4225)$ $A_2 = 0.0917$

$C_3 = (0.0415, 0.0629, 0.1027)$ $A_3 = 0.0724$

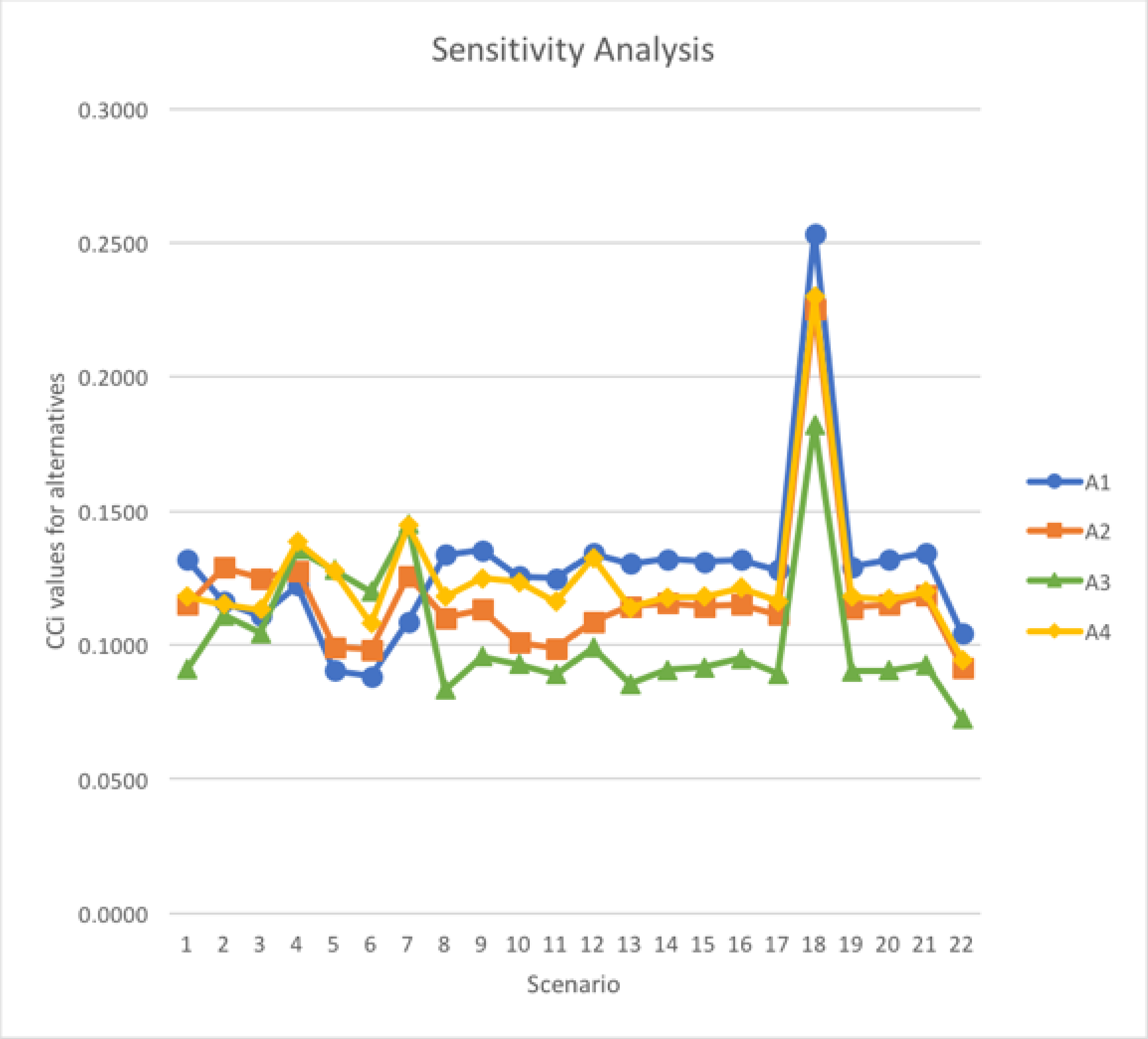
$C_4 = (0.0746, 0.1286, 0.2138)$ $A_4 = 0.0944$

$C_5 = (0.0344, 0.0630, 0.1245)$

$C_6 = (0.0078, 0.0115, 0.0185)$

$C_7 = (0.0231, 0.0446, 0.0817)$

Figure 19. Effect on ranking of alternatives due to sensitivity analysis



It can be clearly observed from table 27 and figure 19 that when weights of evaluation criteria are changed mutually, alternative A_1 which has the highest CC_i value in the original scenario, has maintained its position in 15 scenarios out of 21 scenarios, accounting for approximately 71%. Apart from these scenarios, alternative A_2 takes the lead in two scenarios number 1 and 2, whereas alternative A_4 is the winner in scenarios number 3. In the remaining scenarios number 4, 5 and 6, alternative A_3 reaches the top. These striking changes are attributed to the fact that the weight of the first criterion C_1 is exchanged with criterion C_2, C_3, C_4, C_5, C_6, C_7 sequentially. Hence, it can be concluded that the first criterion C_1 is the most influential in the proposed framework.

Chapter 6. Discussion and conclusion

6.1 Results and discussion

In terms of aspects, economic is the most preferable by the decision makers compared to environmental and social aspect. It is not surprising since the profitability attaches the most attention of decision makers (shipowners and operators). In the economic aspect, the capital cost plays a pivotal role when considering the selection of technological alternatives to meet tightening regulations. The impact on SO_x reduction criteria attracts the highest priority in environmental aspect, followed by the impact on NO_x reduction criteria. This is attributed to the existing regulation on sulphur emissions (0.1% sulphur content limit in ECAs since January 2015 and 0.5% sulphur content limit in the globe since January 2020) as well as NO_x emissions regulation (Tier III) for new-build ships in ECAs. The impact on GHG reduction and the impact on PM reduction criteria are not given the shipowners' interest because there the Kyoto protocol legislation does not impose penalties on GHG emissions from the shipping industry and there are no regulations on PM emissions yet. There is increasing concern for the marine environment and new measures have been and will be implemented continuously to preserve the oceans and seas. It is critical to emphasize that in the future, there will be legislation on GHG emissions from shipping sector even with low-sulphur and low-nitrogen fuels.

According to the closeness coefficient CC_i values, the ranking of the alternative technologies are Low sulphur fuels, Methanol, HFO with scrubbers and LNG from the most preferable to the least preferable. Low-sulphur fuels are recognized as the best solution for regulatory compliance Methanol is the runner-up in the prioritization of alternatives meanwhile scrubbers and LNG appear not to be very attractive, standing in two last positions.

The outcomes of sensitivity analysis indicate that the weight of the criterion C_1 Capital cost has significant on the stability in the ranking of most and least alternatives. This is due to the strong decision-makers' preferences over this criterion. It is undeniable that capital cost is the most important factor of ship operators when it comes to investment decision on selecting emissions reduction measures. The results of alternative ranking reflect the current situation of shipping industry in which inertia and financial issues are taken into account. Low-sulphur fuels are likely to be a mainstream solution for regulatory compliance in terms of 2020 global sulphur limits (PLATSS, 2017). Furthermore, the results are also in line with the results of some studies in literature, in which Low-sulphur are regarded as the best option in the short-term (Helfre & Boot, 2013; (Ren & Lützen, 2015). In the medium and long run, shipowners and operators should consider potential future regulatory changes and actual conditions to decide on which path they should follow based on their preferable interest.

6.2 Conclusion

Selecting technological alternatives for regulatory compliance towards reducing emissions from ships is MCDM issue which refers to prioritizing a finite number of feasible alternatives with respect to multiple criteria evaluation. It is more challenging for decision makers when they deal with fuzzy environment of vague, incomplete and inconsistent information. A number of approaches has been proposed to tackle the MCDM problem such as ELECTRE, DEA, VIKOR, PROMETHEE, AHP, ANP, TOPSIS, etc. In this study, the integrated fuzzy MCDM approach was proposed by combining fuzzy AHP and fuzzy TOPSIS techniques which are quite simple in conception and application in comparison with other methods for MCDM analysis. The proposed fuzzy approach after that was applied on a real study case by engaging ship-owners as decision makers. Their involvement and interactions were considered in two phases. First, after identifying and evaluating criteria and feasible alternatives, they were requested to assign the importance of the different aspects and criteria by pairwise comparison. Second, they were required to rate the performances of alternatives with respect to criteria. The weights of evaluation criteria produced by the fuzzy AHP were used as inputs in the fuzzy TOPSIS. The linguistic variables were employed in the evaluation process and then converted into fuzzy numbers afterwards in order that the evaluation process to be more realistic since it has fuzziness and incompleteness in its nature. Nine criteria in three aspects along with four feasible alternatives are mentioned in the proposed method, aiming at prioritizing the alternatives from the best to the worst.

According to results of the study, Low sulphur fuels took the lead, followed by Methanol. Scrubbers and LNG were the third and fourth solution respectively. Sensitivity analysis was also deployed to discuss and elaborate the results. The outcomes of sensitivity analysis indicate that this proposed decision-making framework is robust except for the changes of the weight of criterion Capital cost with another criterion.

This study proposed the comprehensive and holistic integrated fuzzy MCDM approach for selecting the best alternative in spite of conflicting criteria. Therefore, the contribution of this study is to propose a useful decision-support tool for the evaluation and prioritization of technological alternatives for regulatory compliance towards emissions reduction from shipping under vague environment. This proposed method can be applied to other fields where decision-makers can use this method to make decision under vague information conditions.

There are several drawbacks of the proposed method. Firstly, the fuzzy AHP may involve the subjectivity of decision makers in their judgements during assigning preferences of one criterion over another criterion. Hence, the quality of experts with their expertise and experience play a vital role when evaluating the criteria in the proposed methodology since experts with different backgrounds and perspectives may display different viewpoints, leading to bias in input data. Another disadvantage of the fuzzy AHP technique is that it may assign unreasonable zero weights to decision criteria attributed to the peculiarity of the method. However, the fuzzy AHP has still been widely used in the literature. In addition, all input data of alternatives with respect to criteria were described as fuzzy numbers for the application of the fuzzy AHP to resolve the severe ambiguous and uncertain MCDM problem. However, some of them could be depicted by crisp numbers that are obtainable from the literature, reports and they could not be fully used.

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APPENDICES

Appendix A. Questionnaire form to facilitate the pairwise comparison of aspects with regard to goal

How important is aspect Economic when it is compared with aspect Environmental?

How important is aspect Economic when it is compared with aspect Social?

How important is aspect Environmental when it is compared with aspect Social?

Please tick (X) as appropriate.

Aspect comparison							
Aspect	Compare the important weights of aspects with regard to the goal						Aspect
	Just equal	Equal important	Week important	Strong important	Very strong important	Extremely important	
Economic							Environmental
Economic							Social
Environmental							Social

Appendix B. Questionnaire form to facilitate the pairwise comparison of each criterion with regard to another criterion

How important is criterion Capital cost when it is compared with criterion Operational cost?

How important is criterion Capital cost when it is compared with criterion Life-cycle cost?

How important is criterion Operational cost when it is compared with criterion Life-cycle cost?

Please tick (X) as appropriate.

Economic Criteria							
Criterion	Compare the important weight with regard to the different criteria						Criterion
	Just equal	Equal important	Week important	Strong important	Very strong important	Extremely important	
Capital cost							Operational cost
Capital cost							Life-cycle cost
Operational cost							Life-cycle cost

How important is criterion Reduction of SO_x emissions when it is compared with criterion Reduction of NO_x emissions?

How important is criterion Reduction of SO_x emissions when it is compared with criterion Reduction of GHG emissions?

How important is criterion Reduction of SO_x emissions when it is compared with criterion Reduction of PM emissions?

How important is criterion Reduction of NO_x emissions when it is compared with criterion Reduction of GHG emissions?

How important is criterion Reduction of NO_x emissions when it is compared with criterion Reduction of PM emissions?

How important is criterion Reduction of GHG emissions when it is compared with criterion Reduction of PM emissions?

Please tick (X) as appropriate.

Environmental Criteria							
Criterion	Compare the important weight with regard to the different criteria						Criterion
	Just equal	Equal important	Week important	Strong important	Very strong important	Extremely important	
Reduction of SOx emissions							Reduction of NOx emissions
Reduction of SOx emissions							Reduction of GHG emissions
Reduction of SOx							Reduction of PM

emissions							emissions
Reduction of NOx emissions							Reduction of GHG emissions
Reduction of NOx emissions							Reduction of PM emissions
Reduction of GHG emissions							Reduction of PM emissions

How important is criterion Government and industry support when it is compared with criterion Externalities?

Please tick (X) as appropriate.

Social Criteria							
Criterion	Compare the important weight with regard to the different criteria						Criterion
	Just equal	Equal important	Week important	Strong important	Very strong important	Extremely important	
Government and industry support							Externalities

Appendix C. Questionnaire form to facilitate the performance ratings of alternatives with respect to criteria

With regard to Capital cost criterion, what is your rating on Low sulphur fuels alternative based on the rating scale below?

And so on…

Please tick (X) as appropriate.

Economic Criteria	Alternative	Rating				
		Very poor	Poor	Fair	Good	Very Good
Capital cost	Low sulphur fuels					
	HFO with scrubber					
	LNG					
	Methanol					
Operational cost	Low sulphur fuels					
	HFO with scrubber					
	LNG					

	Methanol					
Life-cycle cost	Low sulphur fuels					
	HFO with scrubber					
	LNG					
	Methanol					

With regard to Reduction of SO_x criterion, what is your rating on Low sulphur fuels alternative based on the rating scale below?

And so on…

Please tick (X) as appropriate.

Environmental Criteria	Alternative	Rating				
		Very poor	Poor	Fair	Good	Very Good
Reduction of SO_x	Low sulphur fuels					
	HFO with scrubber					
	LNG					

	Methanol					
Reduction of GHG	Low sulphur fuels					
	HFO with scrubber					
	LNG					
	Methanol					
Reduction of NO_x	Low sulphur fuels					
	HFO with scrubber					
	LNG					
	Methanol					
Reduction of PM	Low sulphur fuels					
	HFO with scrubber					
	LNG					

	Methanol					

With regard to Government and industry support criterion, what is your rating on Low sulphur fuels alternative based on the rating scale below?

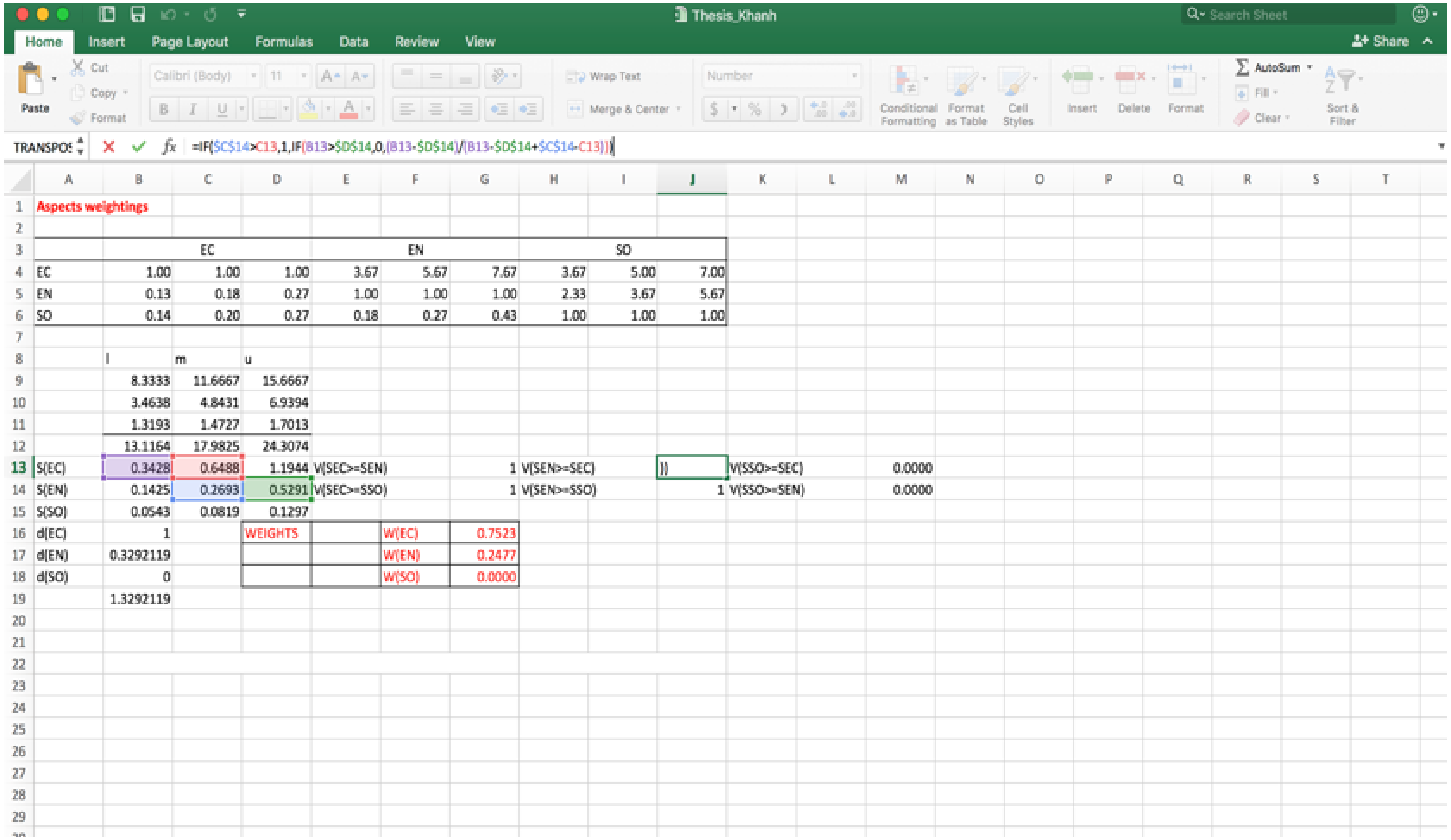
And so on…

Please tick (X) as appropriate.

Social Criteria	Alternative	Rating				
		Very poor	Poor	Fair	Good	Very Good
Government and industry support	Low sulphur fuels					
	HFO with scrubber					
	LNG					
	Methanol					
Externalities	Low sulphur fuels					
	HFO with scrubber					
	LNG					

	Methanol					

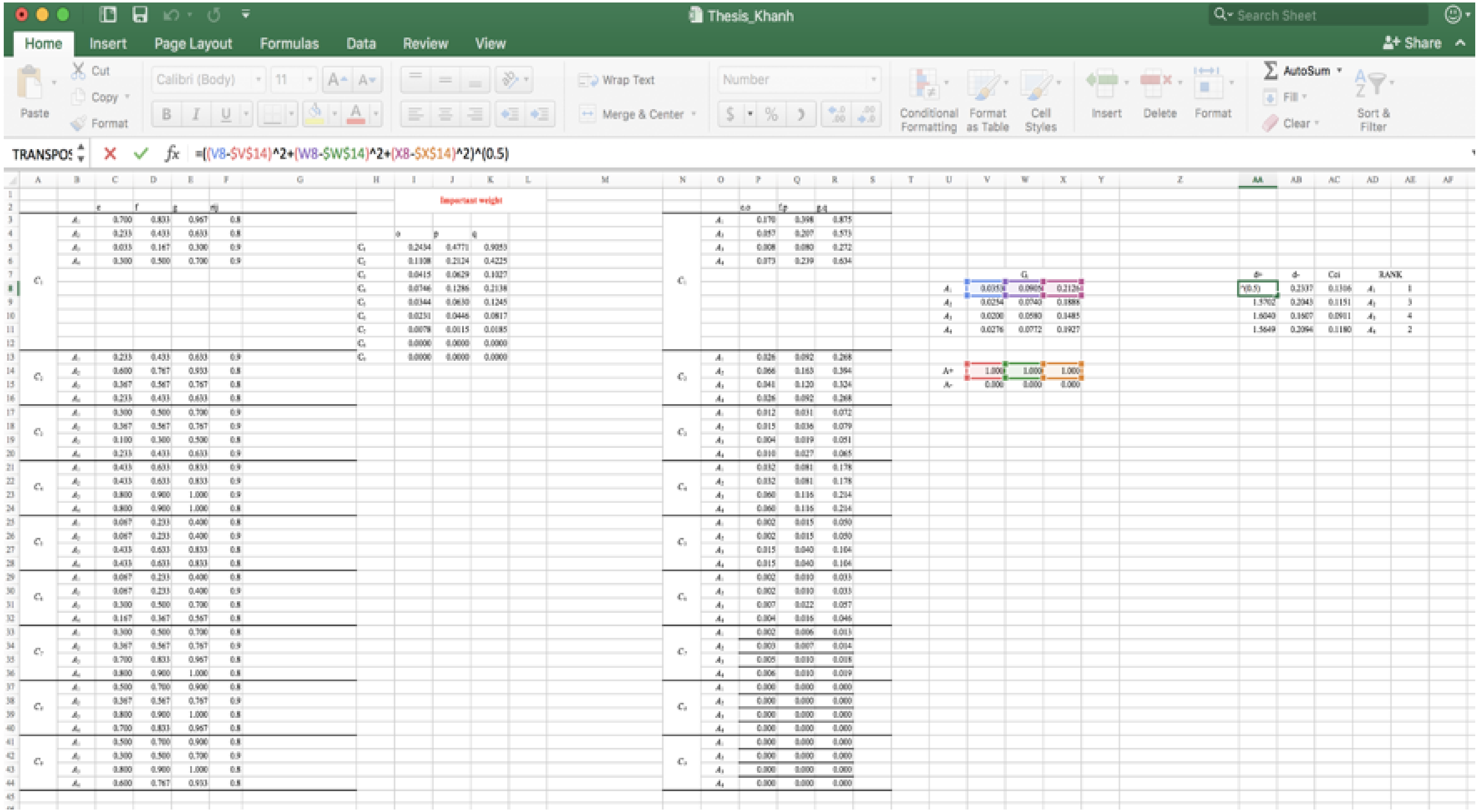
Appendix D. Excel template for determining weights of aspects and criteria using FAHP



```
=IF($C$14>C13,1,IF(B13>$D$14,0,(B13-$D$14)/(B13-$D$14+$C$14-C13)))
```

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Aspects weightings												
2													
3			EC			EN			SO				
4	EC	1.00	1.00	1.00	3.67	5.67	7.67	3.67	5.00	7.00			
5	EN	0.13	0.18	0.27	1.00	1.00	1.00	2.33	3.67	5.67			
6	SO	0.14	0.20	0.27	0.18	0.27	0.43	1.00	1.00	1.00			
7													
8		l	m	u									
9		8.3333	11.6667	15.6667									
10		3.4638	4.8431	6.9394									
11		1.3193	1.4727	1.7013									
12		13.1164	17.9825	24.3074									
13	S(EC)	0.3428	0.6488	1.1944	V(SEC>=SEN)		1	V(SEN>=SEC)		))	V(SSO>=SEC)		0.0000
14	S(EN)	0.1425	0.2693	0.5291	V(SEC>=SSO)		1	V(SEN>=SSO)		1	V(SSO>=SEN)		0.0000
15	S(SO)	0.0543	0.0819	0.1297									
16	d(EC)	1		WEIGHTS		W(EC)	0.7523						
17	d(EN)	0.3292119				W(EN)	0.2477						
18	d(SO)	0				W(SO)	0.0000						
19		1.3292119											

Appendix E. Excel template for ranking alternatives using FTOPSIS



=((V8-V14)^2+(W8-W14)^2+(X8-X14)^2)^(0.5)