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WORLD MARITIME UNIVERSITY
Malmö, Sweden

Fuzzy multi-criteria decision-making approach for technology selection for emissions reduction from seaborne transportation under uncertainty and vagueness

By

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ALGERIA

A dissertation submitted to the World Maritime University in partial fulfilment of the requirements for the reward of the degree of

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in
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(MARITIME ENERGY MANAGEMENT)

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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.

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Abstract

Title of Dissertation: **Fuzzy multi-criteria decision-making approach for technology selection for emissions reduction from seaborne transportation under uncertainty and vagueness**

Degree: **Master of Science**

The trend towards sustainability and decarbonisation is increasingly gaining traction in shipping industry due to more stringent environmental regulations and the collective will from society around the world. The global sulphur regulation that came into effect in 2020 has become a pivotal figure in terms of fuel choices in the maritime industry. Decision-makers (ship-owners and ship operators) will have to choose fuel pathways in the future. In fact, the selection of a suitable alternative is a significant concern for decision makers. In this process, a number of conflicting criteria need to be considered as well as its complexity, which can be modelled as a multi-criteria decision-making (MCDM) problem. Considering the vagueness and imprecision often represented in decision data due to the lack of complete information and the ambiguity arising from the qualitative judgment of decision-makers when evaluating alternatives. Such an analysis involves a fuzzy concept into MCDM where prioritization of a set of feasible alternatives vis-à-vis a multi criteria evaluation is undertaken under vague environment. This study proposes an MCDM framework comprising Fuzzy Analytic Hierarchy Process (AHP), VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), and Technique for Order Performance by Similarity to Ideal Solution (TOPSIS), for technology selection for regulatory compliance towards emissions reduction from shipping under uncertainty and vagueness. Nineteen (19) criteria integrated into five (5) sustainability assessment factors (Technical, Environmental, Economic, Other-factors, and Social-political) were selected. Fuzzy AHP was employed to determine the priority weights of aspects/criteria and the performance of alternatives with regard to each criterion. Afterwards, alternatives were prioritized by VIKOR and TOPSIS. Based on the proposed framework outputs, Low-Sulphur Fuels are ranked as the best comprise solution for regulatory compliance. Scrubbers, Liquefied natural gas (LNG), Methanol and Ammonia follow in order, respectively. Sensitivity analysis was performed to validate the robustness of the results by varying the weights of the criteria. The proposed framework is an efficient and effective decision support model and can also be used for similar regulatory compliance problems in other modes of transportation.

KEYWORDS: Seaborne transportation, Emissions reduction, Alternative technologies, MCDM, Fuzzy AHP, VIKOR, TOPSIS

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List of Abbreviations

AHP	Analytic Hierarchy Process
BC	Black Carbone
CAPEX	Capital cost
CH_4	Methane
CO_2	Carbon dioxide
CII	Carbon intensity indicator
ECAs	Emission control areas
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
ELECTRE	Elimination and Choice Translating Reality
EU	European Union
NIS	Negative Ideal Solution
PIS	Positive Ideal Solution
GHG	Greenhouse Gases
GWP	Global warming potential
HFO	Heavy fuel oil
IMO	International Maritime Organization
IPCC	International Plant Protection Convention
LNG	Liquefied Natural Gas
LSFO	Low Sulphur Fuel Oil
MARPOL 73/78	The International Convention for the Prevention of Pollution from Ships
MCDM	Multi-criteria decision-making
MEPC	Marine Environment Protection Committee
MRV	Monitoring, Reporting and Verification
NECAs	Nitrogen oxide emission control areas
NH_3	Ammonia
NO_X	Nitrogen oxides
OPEX	Operational cost

PM	Particular Matter
PROMETHEE	Preference Ranking Organization Method for Enrichment and Evaluations
SECAs	Sulphur emission control areas
SEEMP	Energy Efficiency Management Plan
SO_X	Sulphur oxides
TOPSIS	Technique for Order Performance by Similarity to Ideal Solution
VIKOR	Viekriterijumsko Kompromisno Rangiranje
WMO	World Meteorological Organization

Chapter 1. Introduction

1.1 Background

Maritime transportation is vital to the global economy. It is the most cost-efficient mode of transport (long-distance) per tonne-kilometre of freight transported (GloMEEP, 2018; Raza, 2020); and, in many cases, the only practical way to deliver goods around the world efficiently and economically (McCarney, 2020). Global maritime trade is expanding as international trade demand increases. An average annual growth rate of 3.5% is foreseen over 2019-2024 (Karam et al., 2020). While seaborne transportation only uses 7% of all energy consumed by global transportation movements (Nogué-Algueró, 2019), it contributes around 90% of international trade (ICS, 2020). International shipping has certain pros and cons. Although perceived as the most energy-efficient mode of transportation compared to other modes such as rail and road (Stalmokaitė, 2021), maritime transportation is also a major source of pollution. It contributes significantly to air emissions (Zhu and Wang, 2021). Shipping emissions negatively impact the planet; nonetheless, the maritime sector faces a major challenge in reducing these atmospheric gases (Poulsen et al., 2021). This is mainly due to the shipping industry still being powered by massive fossil fuels. Around 370 million tonnes/year (fuel oil equivalents) are consumed annually by maritime transportation (Herdzik, 2021), combined with the lack of technology available to completely remove gases emissions from ships (Ölçer, 2018). Therefore, air emissions associated with international shipping will continue to be a thorny issue for the shipping industry for the next decades.

Emissions being released into the atmosphere from maritime transportation can be divided into two major categories of gases. Firstly, greenhouse gases (GHG), such as carbon dioxide (CO_2) and methane (CH_4), are responsible for climate change. For instance, international shipping currently accounts for about 3% of total global greenhouse gas (GHG) emissions, but would continue to rise as transport capacity expands (Chen et al., 2019); in which nearly 2% of global energy-related CO_2

emissions per year (Müller-Casseres et al., 2021). Secondly, non-greenhouse gases, such as sulphur dioxide (SO_X), nitrogen oxides (NO_X), and particulate matter (PM), including black carbon (BC); which are responsible for poor air quality and health problems (Tang, et al., 2020). Distinct forms of PM negatively impact human health and the environment; on the other hand, SO_X and NO_X emissions have both acidifying and eutrophication effects (Bui & Perera, 2020a). It has been estimated that ships emit 0.9 million metric tonnes of PM into the atmosphere and account for 20-28% of total air pollutant emissions from the transportation sector (Mousavi et al., 2018). For instance, shipping represents 15% and 4–9% of global NO_X and SO_X emissions, respectively (Toscano & Murena, 2019; Lee et al., 2020); and 2% of global BC emissions (Yacout, et al., 2021). BC is generally known as soot. It has a strong positive radiative forcing in the atmosphere and is a major contributor to climate change (Takemura & Suzuki, 2019, Åström et al., 2021). These atmospheric emissions emitted by ships are expected to increase considerably in the future (EC, 2020); indeed, they are forecasted to more than triple between 2020 and 2050 without further actions (Gössling et al., 2021). In fact, total GHG emissions from ships increased by around 9,6 % between 2012 to 2018 despite improvements in the carbon intensity of international shipping, which ranged from 21% to 32% better than in 2008, and saw a sharp increase in short-lived climate pollutants, such as BC and methane emissions (IMO, 2021). There was an increase of approximately 12% in BC emissions (Psaraftis & Kontovas, 2020; KPMG, 2021); and about 150% growth in methane emissions (Lindstad et al., 2020; EP, 2020). These gases contribute considerably to the warming of the atmosphere (Zhang et al., 2018). According to WMO (2021), global warming continues to increase steadily, and 2020 was one of the hottest years on record; hence, keeping the global average temperature between 1.5 ° C and 2 ° C, outlined in the Paris Climate Agreement, above pre-industrial levels by the end of this century will require an effective global plan to reduce further air emissions. While to achieve the Paris objectives the maritime sector should reduce its GHG emissions by at least 50% by 2050 compared to 2008 and eliminate them thereafter (Christodoulou et al., 2021), significant reductions in methane and BC emissions of 35% or more of both by 2050 compared to 2010 will also be required (IPCC, 2019; Comer, 2019). Therefore, a shift to cleaner and more energy-efficient solutions will be needed for shipping to meet its ambitious emissions targets.

Efficiency, linked to GHG and air pollution emissions, has been an issue within the IMO for a long time (IMO, 2016). Regarding the control of GHG emissions, IMO has been proactive in updating Chapter 4 of Annex VI of the International Convention for the Prevention of Pollution from Ships (MAROPOL) by introducing mandatory technical and operational measures for the control of emissions from ships, entered into force on January 1, 2013 (Anh Tran, 2016). The first measure is a technical standard represented by the Energy Efficiency Design Index (EEDI) that aims at promoting the use of innovative technologies when designing and building new ships in phased approach to reduce carbon intensity expressed in grams of CO_2 per ship's capacity-mile (Stec et al. 2021); the second, the operational measure described by the Ship Energy Efficiency Management Plan (SEEMP) that provides a mechanism to improve the energy efficiency of ships in a cost-effective manner by implementing new technologies and best practices on board ships (Hansen et al., 2020). Furthermore, the initial IMO´s GHGs strategy was established by IMO in 2018 in accordance with the goals of the Paris Agreement. This ambitious IMO 2050 target sets out a vision to halve at least GHG emissions from international shipping by 2050 from their 2008 level and work towards their complete elimination as soon as possible over the course of this century (Joung et al., 2020). In addition, two data-driven approaches to reduce GHG emissions from ships introduced by the European Union (EU) and IMO (Panagakos et al., 2019; Kanberoğlu & Kökkülünk, 2021). The former is EU Monitoring, Reporting and Verification (EU MRV), which began collecting data from 1 January 2018 and tackles CO_2 emissions from maritime sector activities to, from and within the EU waters; the latter, namely the Data Collection System (IMO DCS), which started collecting data from 1 January 2019 and deals with emissions from maritime sector activities on a global scale (Rony et al., 2019). In 2021, two associated IMO indexes-EEXI and CII- have been adopted as amendments to MARPOL-

Annex VI, taking effect from 2023. The first index is a retroactive and extended application of the EEDI to all existing ships, called Energy Efficiency Existing Ship Index (EEXI); the second is an annual operational carbon intensity indicator (CII) and rating scheme to provide ship-owners with a benchmark to reduce their levels and get on track to meet IMO´s emissions targets (DNV, 2021). While CH_4 emissions from international shipping, mainly related to methane slip, have become an issue due to the growth in the use of LNG as a marine fuel, there are increasingly more requests submitted to IMO to regulate methane emissions (IMO, 2020). Accordingly, including CH_4 in IMO's EEDI regulations in future phases will be a step forward in tackling methane emissions from shipping (Lindstad & Rialland, 2020). Therefore, new regulations to mitigate methane emissions from marine engines are expected shortly.

Unlike GHG emissions, controlling the environmental impacts of SO_X, NO_X, and PM emissions is necessary to achieve IMO targets as well as to sustain the global environment and the well-being of population. Accordingly, Emission Control Areas (ECAs) were introduced in Chapter 3 of Annex VI of MARPOL (Bui & Perera, 2020b). Since January 1, 2015, the sulphur requirement has been set within the limits of the ECAs at 0.1% m/m on the sulphur content of fuel oil for ships (Yang et al., 2021; McCaffery et al. 2021). On January 1, 2020, the global sulphur cap, IMO 2020 regulation came into effect. This regulation sets limits of 0.5% m/m limits on the sulphur content of marine fuel oil; considering the three main key compliance options such as LNG (Liquefied Natural Gas), LSFOs (Low Sulphur Fuel Oils), and HFO (Heavy Fuel Oil) combined with Exhaust Gas System (EGS), commonly known by scrubber (Sáez ÁLvarez, 2021). While aiming to control and investigate marine pollution due to the use of scrubbers on-board ships, in 2005 IMO adopted the first IMO guidelines for scrubber wash-waters (Resolution MEPC.130(53)) and introduced the first discharge criteria for water pollutants in 2008 as revisions to the guidelines (Resolution MEPC.170(57). Indeed, the guidelines were revised in 2009, 2015, and 2020, but not tightened (Comer et al., 2020). On the other hand, NO_X emission limits have also been introduced with three distinct levels of compliance, namely Tier I, Tier II, and Tier III standards, applying to marine diesel engines according to the maximum engine speed, installed on-board ships with different construction dates. The Tier III standards only apply to NO_X ECAs, while Tier I and Tier II limits are global (Perčić et al., 2020; Lu et al., 2021). New NO_X ECAs have been designed from 1 January 2021; such as, the Baltic Sea and the North Sea (Dall'Armi et al., 2021). While the control of BC emissions has recently emerged as a priority issue on the environmental agenda for IMO, a binding international policy aims at limiting BC emissions throughout the polar region is expected soon (Kong et al., 2021, Comer et al., 2020). In fact, a ban on the use of high black-carbon fuels such as HFO in the arctic waters after July 1, 2024, has been approved by IMO´MEPC 76 (ABS, 2021). In addition, black-carbon-based fuels would be extended to VLSFOs (blends) directly impacting the increase in BC emissions from ships (IMO, 2021). Thus, environmental regulations are increasingly stringent and progressing.

The aforementioned stricter environmental regulations will raise concerns among decision-makers about most suitable alternative compliant options that should be adopted on board their ships for regulatory requirements towards emission reduction from shipping. In fact, as IMO calls for wide adoption of cleaner alternative technologies on-board ships, following other energy efficiency measures, to meet its emission targets (Serra & Fancello, 2020; Christodoulou et al., 2021), many shipping companies are looking for the best trade-offs to consider on board ships to achieve the set goals (Irena et al., 2021). Although several alternative technologies, for example Ammonia and Methanol, have been considered potential alternative fuels for maritime transportation to achieve IMO´s sustainability goals (Ben Brahim et al., 2019), there are problems of uncertainly and vagueness in the decision making when evaluating alternative fuels for regulatory compliance (Shell, 2020). These are mainly related to the lack of relevant information and data among decision makers; combined with unpredictable volatility in fuel prices in the post-IMO2020 era (Zis & Cullinane,2020).

Accordingly, selecting the best alternative for regulatory compliance involves a multi-criteria decision-making analysis (MCDM), where prioritizing a potential set of alternatives vis- à-vis a multi-criteria analysis is undertaken. This also requires selecting the best suitable MCDM method. Two widely known ranking techniques in the literature are mainly applied in the MCDM problems, such as VIKOR (Multi-criteria Optimization and Compromise Solution) and TOPSIS (Technique for Order Performance by Similarity Ideal Solution). Thus, integrating fuzzy AHP (Analytic Hierarchy Process), which has the possibility of obtaining the criteria weightings and the relative performance of alternatives with regards to each evaluation criterion under vague environment, with VIKOR and TOPSIS will lead to an in-depth analysis on the final ranking of alternatives.

1.2 Problem statement

Shipping industry is now experiencing constant international pressure to comply with an increasingly stringent regulatory environment, coupled with volatile and expensive fuel oils. With the rapid development of new technologies, alternative fuels have been identified as promising solutions to achieve IMO regulatory framework for ship emissions. Nevertheless, decision-makers are challenged by the difficult task of selecting the most suitable solutions on board their ships. These are mainly due to the inaccurate incorporations of the preferences of the decision-makers and the problems of uncertainty that exist in the evaluations of alternatives towards emissions reduction. Therefore, there is a need to improve on similar studies already published to help decision-makers achieve their goals and reach a conclusion on the most preferred energy pathways in the near future.

1.3 Aims and objectives

The present research study aims to develop an MCDM model for technology selection for emissions reduction from shipping under uncertainty and vagueness. This MCDM framework will help decision-makers (ship-owners and operators) to choose the best alternative technologies on-board ships for regulatory compliance.

1.4 Research questions

The following research questions are selected to achieve the objectives of this study:

- What are the alternative technologies available to decision-makers for meeting current and future environmental regulations?
- What are the factors influencing decision-makers on the choice of an alternative technology?
- How can decision-makers prioritize alternative technologies in a context of imprecision and incompleteness of data?

1.5 Research methodology

Both quantitative and qualitative approaches are involved in this research study. This study is expected to provide useful insights for the design and development of a fuzzy-MCDM framework integrating three techniques: fuzzy AHP, VIKOR and TOPSIS. Fuzzy AHP is employed to determine the weight of attributes (criteria and aspects), representing the relative importance of the evaluation criteria in the decision-making process, and the relative performance of alternatives with respect to each criterion. Subsequently, VIKOR and TOPSIS are used to prioritize the alternative technologies for selecting the best solutions for emissions reduction from shipping.

The qualitative method in this study is represented by a semi-structured interview. Questionnaire forms are used to facilitate pairwise comparisons with respect to different attributes and for the alternatives with regard to each evaluation criterion, allowing decision makers to use linguistic terms according to their preferences when evaluating the attributes and alternatives.

1.6 Expected results

A generic MCDM model is expected to be developed to help decision-makers select the best alternative technology for regulatory compliance towards emissions reduction from shipping. This model includes a system of evaluation criteria comprising five (5) factors (e.g., environmental, economic, and social). Thus, to demonstrate the effectiveness of the MCDM model, a case study will be presented considering five (5) feasible alternative technologies (e.g., LNG, Methanol, and Ammonia).

1.7 Organisation of study

This study is split into 5 chapters. Chapter 1 is a general introduction combining the background and overview of the research study, such as the problem statement and the research questions. Followed by Chapter 2, which describes the literature review on the MCDM problem. Chapter 3 discusses the methodology with the proposed MCDM model, integrating the three methods such as fuzzy AHP, VIKOR, and TOPSIS to prioritise alternative technologies for emissions reduction from maritime transportation. Afterwards, Chapter 4 demonstrate the effectiveness and efficiency of the developed MCDM framework in ranking alternatives under uncertainty and vagueness through a case study. Finally, Chapter 5 presents the summary and conclusion.

Chapter 2. Literature review

2.1 Review on MCDM Models

Multi-Criteria Decision Making (MCDM) methods in the maritime research domain became effective and popular solutions to help decision-makers reach a rational decision under uncertainty. Analytical Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), VIsekriterijumska optimizacija i KOmpromisno Resenje (VIKOR), ELECTRE (Elimination and Choice Translating Reality) and PROMETHEE (Preference Ranking Organization Method for Enrichment and Evaluations) are the standard frameworks of the most well established MCDM methodologies (Qu et al., 2017). These methods present a set of techniques applied to certain criteria to identify, compare and evaluate alternatives; in addition, they can be combined as a crisp framework applied to rank alternatives (Dammak et al., 2016). Nevertheless, the use of crisp values in the non-fuzzy environment in MCDM problems are not appropriate in many cases when considering the vagueness, imprecision and ambiguity arising from the qualitative judgment of decision-makers (Guo et al., 2017). This can be compensated through the use of fuzzy set theory (Kim and Sea, 2019). Accordingly, the mathematic fuzzy logic tool, known as fuzzy set theory, which Zadeh developed in 1965, was introduced in MCDM methods (Kahraman, 2008). Therefore, fuzzy-MCDM Models were developed and introduced in the literature.

AHP is the most widely used method in MCDM frameworks as an approach employed to quantify the decision criteria' weights; in binary comparison through square matrix obtained by using the scale graded 1-9 representing expert opinions (Doğan & Akbal, 2021; Efecan & Temiz, 2019). Although the AHP technique allowing for a hierarchical structure of criteria, which help users to better focus on specific criteria and sub-criteria when assigning weights (Ishizaka & Labib, 2009), it has some flaws in a fuzzy environment (Sun, 2010). Researchers integrate fuzzy theory with the AHP technique to overcome these issues to improve the uncertainty and resolve ambiguity and imprecision in human judgment by using the fuzzy linguistic scale and correctly prioritising different criteria (Chang, 1996a; Liu et al., 2020). Nowadays, fuzzy AHP is one of the common methods employed to resolve MCDM problems and is generally used to determine the weights of criteria and the relative importance of alternatives in a structured manner based on a pairwise comparison when subjective judgments during the comparison may be inexact and uncertain, for instance (Celik et al., 2009; ÜNver et al., 2021).

Unlike AHP, TOPSIS and VIKOR techniques, based on the distance from the ideal solution, have become broadly employed for solving MCDM problems and have found use in maritime domains such as environmental management and energy management; for instance (Chai & Ngai, 2020; Sivaraja & Sakthivel, 2017; Demirel et al., 2020; Ross & Schinas, 2019; Nooramin et al.,2012). The TOPSIS method was developed based on the concept that the chosen alternative should have the furthest Euclidean distance from the negative ideal solution (NIS) and the shortest Euclidean distance from the positive ideal solution (PIS) for solving an MCDM problem, where the PIS maximize the benefit criteria and minimize cost criteria (Alpay & Iphar, 2018); nevertheless, it cannot consider the relative importance of these distances (Opricovic & Tzeng, 2004). Due to TOPSIS´s features, such as simplicity, good computational efficiency, and ability to evaluate the relative performance for each alternative in a simple mathematical form (Wang, 2018), it has become a popular technique used by researchers around the world (Kaliszewski & Podkopaev, 2016). Nonetheless, TOPSIS fails to derive weights for the decision criteria, alleviate the requirement for pairwise comparisons, and maintain the consistency check of judgments (Shih et al., 2007). To overcome these shortcomings, TOPSIS is often integrated with the AHP technique and other MCDMs (Karahalios, 2017). Accordingly, an AHP-TOPSIS model, combining the AHP and TOPSIS techniques, is suggested. However, fuzzy AHP-TOPSIS model is the appropriate approach to deal with the problems associated with ambiguous, subjective, and imprecise human judgments under fuzzy based enhancement.

This model is flexible and practical for decision-makers and provides a more precise, efficient, and systematic decision support tool (Hoziari et al., 2019). Indeed, many examples of fuzzy AHP-TOPSIS based frameworks widely used to solve MCDM problems exist in the literature, for instance (Alarcin et al., 2014; Bucak et al., 2021; Ballini et al., 2021). On the other hand, the VIKOR technique was initially developed by Serafim Opricovic and presented as an efficient technique to deal with MCDM problems with conflicting and different criteria (Chang, 2014). VIKOR is a well-known technique employed to solve MCDM problems. It is frequently used and seen as producing solid results (Papathanasiou, 2021; Mardani et al., 2016; Tučník, 2016); mainly due to its simplified method with a small number of steps to compute the ranking of alternatives (Zimonjić et al., 2018); and its advantages over other MCDM methods in terms of accuracy in the final ranking (Fallahpour & Moghassem, 2012). Nevertheless, VIKOR extracts the compromise solution and the compromise ranking list with initial (given) weights (Kraujalienė, 2019). In the VIKOR method, the criteria usually describe the maximization of profit and minimization of expenses (Huang et al., 2021); and the alternatives are evaluated according to all established criteria (Liu et al., 2015). In addition, VIKOR prioritizes the alternatives and drives the compromise closest to the positive ideal solution (PIS) (Akram et al., 2021; Sayadi et al., 2009); accordingly, the results obtained by this method are such that they make trade-offs between desires and possibilities, but also between various interests of decision-makers (Ahmed & Majid, 2019). To improve the reliability and validity of weighting in the VIKOR method, an AHP-VIKOR model integrating the AHP and VIKOR techniques is proposed to assign weights to criteria and rank the alternatives (Zhang et al., 2020; Panwar et al.,2020; Büyüközkan & Görener, 2015); researchers have broadly used this model due to its robustness and efficiency (Siew et al., 2021). Nevertheless, under a fuzzy environment where the uncertainties and subjectivities in judgments are encountered with linguistic variables and represented by fuzzy numbers, fuzzy AHP-VIKOR framework is suggested to solve MCDM problems (Radovanović et al., 2020; Awasthi et al., 2018; Demirel et al., 2020).

Although TOPSIS and VIKOR pursue the same goal of ranking the decision variants (Alternatives), from the best to the worst, the results obtained using both methods often differ (Shekhovtsov & Sałabun, 2020). Notwithstanding, several articles demonstrate that the TOPSIS and VIKOR methods can achieve almost identical results (Chauhan & Vaish, 2014).

Numerous studies have been proposed in the literature to solve MCDM issues, mainly related to regulatory framework for assessment and enhancement of measures to control air emissions and improve energy efficiency on board ships. Yang et al. (2012) employed an AHP-TOPSIS model for selecting NO_X and SO_X emissions control solutions. Schinas & Stefanakos (2014) proposed an AHP based approach for selecting technologies towards compliance with MARPOL Annex VI. Ölçer & Ballini (2015) used TOPSIS technique for evaluation of the trade-off solutions towards cleaner seaborne transportation. Ren & Lützen (2015a) developed a model integrating fuzzy AHP-VIKOR for technology selection for emissions reduction from shipping. Beşikçi et al. (2016) employed fuzzy-AHP to prioritize operational measures within the Ship Energy Efficiency Management Plan (SEEMP) scope. Wang & Nguyen (2016) used a combined method, fuzzy Quality Function Deployment (fuzzy QFD) and fuzzy TOPSIS, to prioritize the mechanism of low carbon shipping measures. Ren & Lützen (2017a) presented a combined Dempster-Shafer theory and trapezoidal fuzzy AHP for alternative sustainability energy source selection for shipping. Ren & Liang (2017) proposed an integrated method combining fuzzy logarithmic least squares and fuzzy TOPSIS to measure the sustainability of alternative marine fuels. Sahin & Yip (2017) employed an improved Gaussian fuzzy AHP model for shipping technology selection for dynamic capability. Animah et al. (2018) used an AHP-TOPSIS model to resolve the shipowners' challenges and compliance with MARPOL Annex VI regulation 14. Bui & Perera (2019a) employed an integrated method combining fuzzy AHP and fuzzy TOPSIS to address compliance challenges for reducing air pollution from shipping. Bui et al. (2020a) used fuzzy-based approach, which integrated fuzzy AHP and TOPSIS to select technological alternatives for regulatory compliance under vague environment. Aspen & Sparrevik (2020) presented an approach based on TOPSIS for evaluating alternative energy carriers in shipping. Tran (2020) proposed fuzzy AHP method to optimize ship energy efficiency management in shipping. In fact, each of the above approaches has advantages and disadvantages. It should be noted that the aforementioned research studies were carried out either with an AHP-TOPSIS model or with an AHP-VIKOR model. Nevertheless, no research study is suggested using both models at the same time. Thus, an integrated model combining fuzzy AHP-TOPSIS-VIKOR is proposed for this research study.

2.2 Criteria for evaluating the sustainability of alternative technologies

Sustainability has recently been one of the main focuses of developments in Industry and society (Karimpour et al., 2019). Experts, policymakers, and activists are working together to achieve the set goal. To meet IMO´s 2050 target, various feasible alternatives for reducing emissions associated with seaborne transportation are proposed in the literature (Perčić et al., 2021; Xing et al., 2021). For instance, LSFOs; LNG; Scrubbers; Methanol; and Ammonia. While many decision-makers are looking for a cost-effective and compliant alternative technology (Andersson et al., 2020), prioritization of alternatives vis-à-vis certain criteria evaluation should also be involved. However, when it comes to evaluating alternative regulatory compliance options, decision-makers (ship-owners and operators) may consider many factors and sub-factors. These factors are primarily based on aspects of sustainable development, generally represented as three pillars: economic, social and environmental, aiming at simultaneously achieving economic prosperity, environmental health and social responsibility (Andersson et al., 2016). In addition, technical and political factors also have been integrated into the sustainability assessment for selecting alternative technologies (Ren & Lützen, 2017b). These two factors influence the pillars of sustainability. While certain sub-factors (e.g., ethics, logistics, and security) can be considered as criteria in the decision-making process for prioritization of alternative options (Bui& Perera, 2019b), other sub-factors (e.g., ship size, ship age, and primary trading area) should also be judiciously analyzed and considered by decision-makers.

These criteria are difficult to categorize into other categories and significantly influence the outcome of the decision making. Thus, decision-makers can consider a large number of sub-factors “criteria” under the aforementioned dimensional factors “aspects” when selecting the most suitable alternatives for emissions reduction from shipping with regard to an evaluation criterion system, as proposed in the following analytical framework.

2.2.1 Technical factor

- Energy efficiency:

Energy efficiency means that every unit of energy used in a ship´s engine translates into greater efficiency or greater service output (EEC, 2019). This can be performed by using the superior physical or chemical properties of alternative fuels, leading to improved engine efficiency and gas emissions (Bae & Kim, 2017).

- Technology reliability:

Technological reliability refers to the reliability of the propulsion systems onboard ships when using the proposed compliant fuel options. This is of the utmost importance, as failures of critical components of ships at sea pose a huge safety risk (Popp & Müller, 2021).

- Safety:

The safety represents the impacts of the proposed alternative fuel options on the crew and the environment in case of leakage or potential human exposure (Hansson et al., 2020); (e.g., Ammonia and Methanol). This is mainly related to bunkering operations, storage and the use of fuel options on-board ships (Hansson et al., 2019).

- Maturity:

The various alternative technologies are currently at different levels of maturity. Amongst these alternatives can be used as fuel in diesel engines with minor or more significant technical changes (ITF, 2018). Nevertheless, some technology alternatives are used commercially, such as LNG and Methanol, some have been tested on-board ships in different pilot projects, some fuels have only been tested in test benches or on a smaller scale or have not reached the stage beyond being discussed (Hansson et al., 2018).

2.2.2 Economic factor

- Profit Margin:

The profit margin refers to the percentage of the total revenue that remains with the ship after deducting all costs when using the proposed alternative technology on-board the ship. The costs are particularly related to the daily fuel consumption prices for the ship's operations (Wu et al., 2021).

- Operational cost

The operating cost represents the expenses related to the day-to-day operation of the vessel, mainly related to the price of fuel, consumables, and maintenance (Bernacki, 2021).

- Capital cost

The capital cost represents upgrading or retrofitting existing vessels to operate alternative technologies such as scrubbers or LNG as a marine fuel, which required investment costs for an existing vessel (Zhu et al., 2020).

- Life cycle cost

The life-cycle cost mentions the costs for manning, building, operating and maintaining over the lifespan of a ship (Favi et al., 2017; Dinu & Ilie, 2015).

2.2.3 Environmental factor

Environmental factor refers to the influence of using the proposed alternative technologies on-board ship to reduce its overall environmental impact (e.g., GHG; $NO_{X;}$ $SO_{X;}$ and BC emissions) (Smith et al., 2019).

2.2.4 Other-factors

- Ship age:

The vessel's age refers to the number of years of service and the vessel's condition, whether retrofitting the proposed alternative technologies is viable and competitive for the vessel during the remaining years of its operation or not. Finding capital to finance proven efficient alternative fuels for shipping can be challenging for some ship-owners, even for technologies that payback for themselves in a few years (Nugroho, 2021).

- Ship size

Vessel size refers to the possibility of adopting the alternative technologies offered on-board a vessel due to the space required. When introducing a new fuel, existing vessels may need to be upgraded or retrofitted. However, issues can arise with small vessels regarding engine space and adaptability (ABS, 2021).

- Primary trading region

The primary trading region represents the main trade zone where the ship is designed to operate first. The availability of the proposed compliant fuel options in and beyond the primary commercial region of the ship, such as bunkering facilities and the supply chain, and the certainty of long-term fuel availability; can help decision-makers consider alternative technologies (Al-Enazi, 2021).

- Other sub-factors

The other sub-factors include sub-factors such as logistics, security, and ethics. Some compliant alternative fuels require further consideration for other concerns. For example, fertilizers such as Ammonia are indispensable for agriculture (Palys et al., 2021). In case of an increased demand for Ammonia as a marine fuel, its production would need to increase significantly (Hansson et al., 2020).

2.2.5 Social-political factor

- Government support

Government support represents the government's initiative and contribution, such as facilitation measures to help decision-makers adopt alternative technologies on-board ships. For instance, a government strategic deployment plan can define a set of subsidiary actions to support the rapid deployment of alternative technologies for a clear policy and the establishment of effective incentives (Ezinna, et al., 2021).

- Externalities:

The externalities represent an environmental assessment of the damage and control costs associated with international shipping to people and the global environment when using the proposed alternative technologies on-board ships. Indeed, seaborne transportation has negative externalities (Vakili et al., 2020). The costs of environmental pollution from ships are mainly related to engine exhaust emissions, especially in port areas, which depend on alternative technologies on-board ships (Dragović et al., 2018; Spengler and Tovar, 2021).

It is noteworthy to highlight the vagueness and inconsistencies of the values of a number of criteria concerning certain alternatives according to the literature. For example, although Ammonia is a carbonless fuel, having no emissions of SO_X and CO_2 (Al-Aboosi, 2021; Cheliotis et al., 2021), there are uncertainties surrounding NO_X and NH_3 slip emissions when using Ammonia as compliant fuel as well as the lack of relevant information on the investment cost of the propulsion system and the operating cost of the ship (ABS, 2020b). While the use of scrubbers can reduce SO_X emissions by more than 95%, and by about 50% to 60% of PM emissions (Zisi et al., 2021), there's uncertainty about their future use as a compliant fuel option. This is mainly due to marine pollution resulting from the discharge of scrubber washwater into the sea (Stokstad, 2021; Comer, 2020; Osipova et al., 2021; Thor et al., 2021; Teuchies et al., 2020)**.** Moreover, giving an example for the vague problem, the economic sub-factors such as the capital cost and operational cost, are difficult to quantify due to fluctuations in fuel oil prices in the market. Furthermore, several criteria tend to be described as intervals instead of crisp numbers; for instance, the values of environmental sub-factors (e.g., impact on NO_X, SO_X, and BC emissions reduction) relative to alternative technologies are shown as intervals rather than crisp values. In addition, some sub-criteria are unquantifiable (e.g., primary trading area, government support, and ethics).

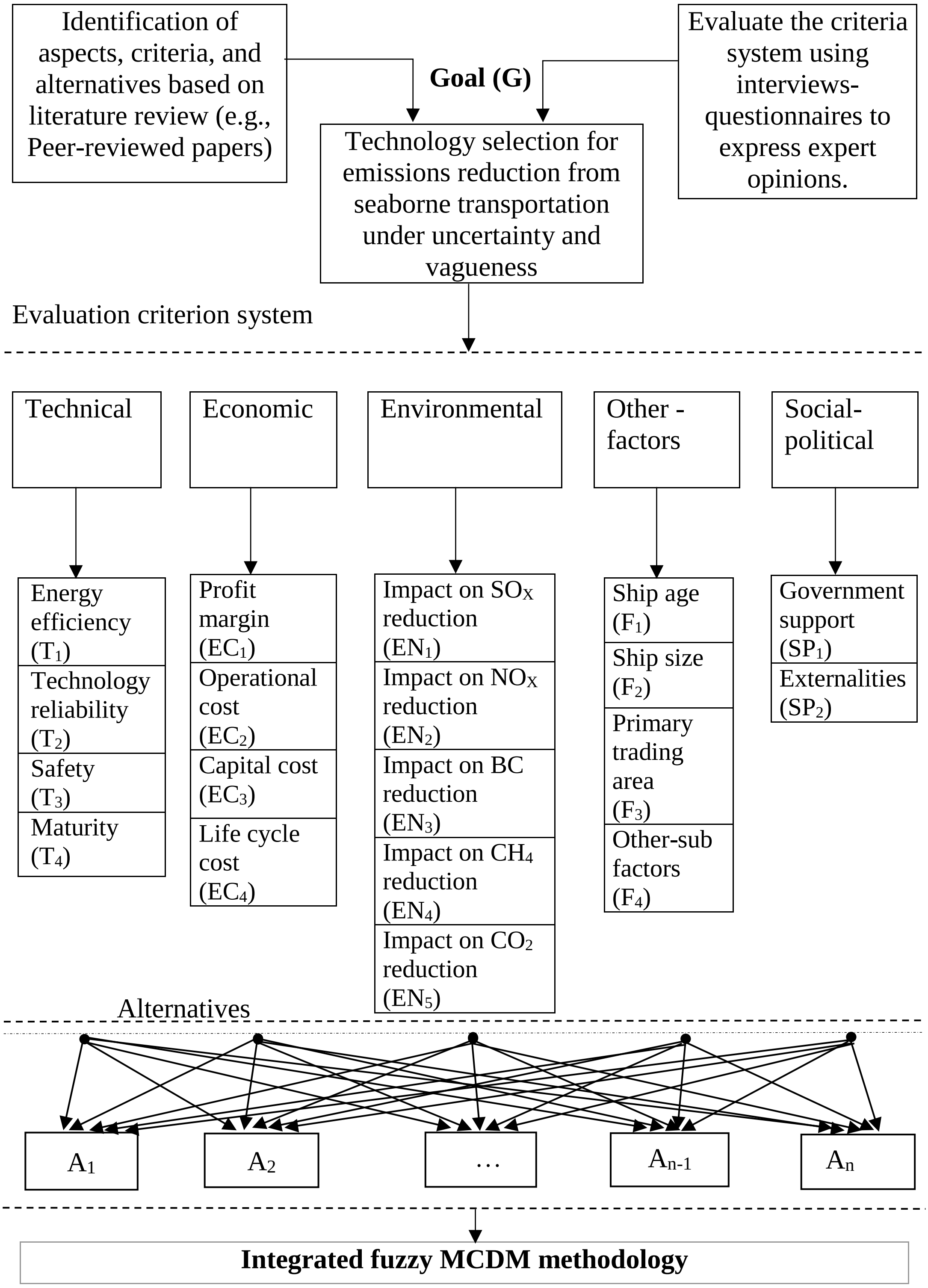
Hence, carrying out the prioritisation of some alternatives based on the proposed evaluation criterion system detailed above involves a multi-criteria decision-making analysis conducted under vague environment. This allows for subjective decision making based on the preferences of the decision-makers. Thus, the proposed MCDM method (Fuzzy AHP, VIKOR and TOPSIS) is a suitable approach to deal with the aforementioned issues. It will be detailed in the following chapter 3.

Chapter 3. Methodology

3.1 The proposed MCDM framework for the evaluation criterion system

An MCDM model is proposed to select the best solution for emissions reduction from shipping under uncertainty and vagueness. The framework is divided into two parts. Part (1) represents an evaluation criterion system, and part (2) describes an integrated fuzzy MCDM methodology. The data in part (1), as illustrated by Figure 1, is designed and structured hierarchically according to the AHP technique. It is used to develop aspects, criteria, and alternatives, which are identified according to the literature review. Accordingly, five (5) feasible alternative technologies (LNG; LSFOs; Scrubbers; Methanol; and Ammonia) and nineteen (19) criteria integrated into five (5) factors were selected in this study. For instance, Economic factor (Capital cost; Operational cost; Life cycle cost; and Profit margin); Environment factor (Impact on the reduction of SO_X emissions; Impact on the reduction of NO_X emissions; Impact on the reduction of CO_2 emissions; Impact on the reduction of BC emissions; and Impact on the reduction of CH_4 emissions); Technical factor (Maturity; Energy efficiency; Technology reliability; and Safety); Other-factors (Ship age; Ship size; Primary trading area; and Other sub-factors); and Social-political factor (Government support and externalities). Externalities can be identified as a cost criterion related to environmental issues linked to maritime transportation. They will be proportional to some of the environmental impacts, such as BC, SO_X and NO_X emissions.

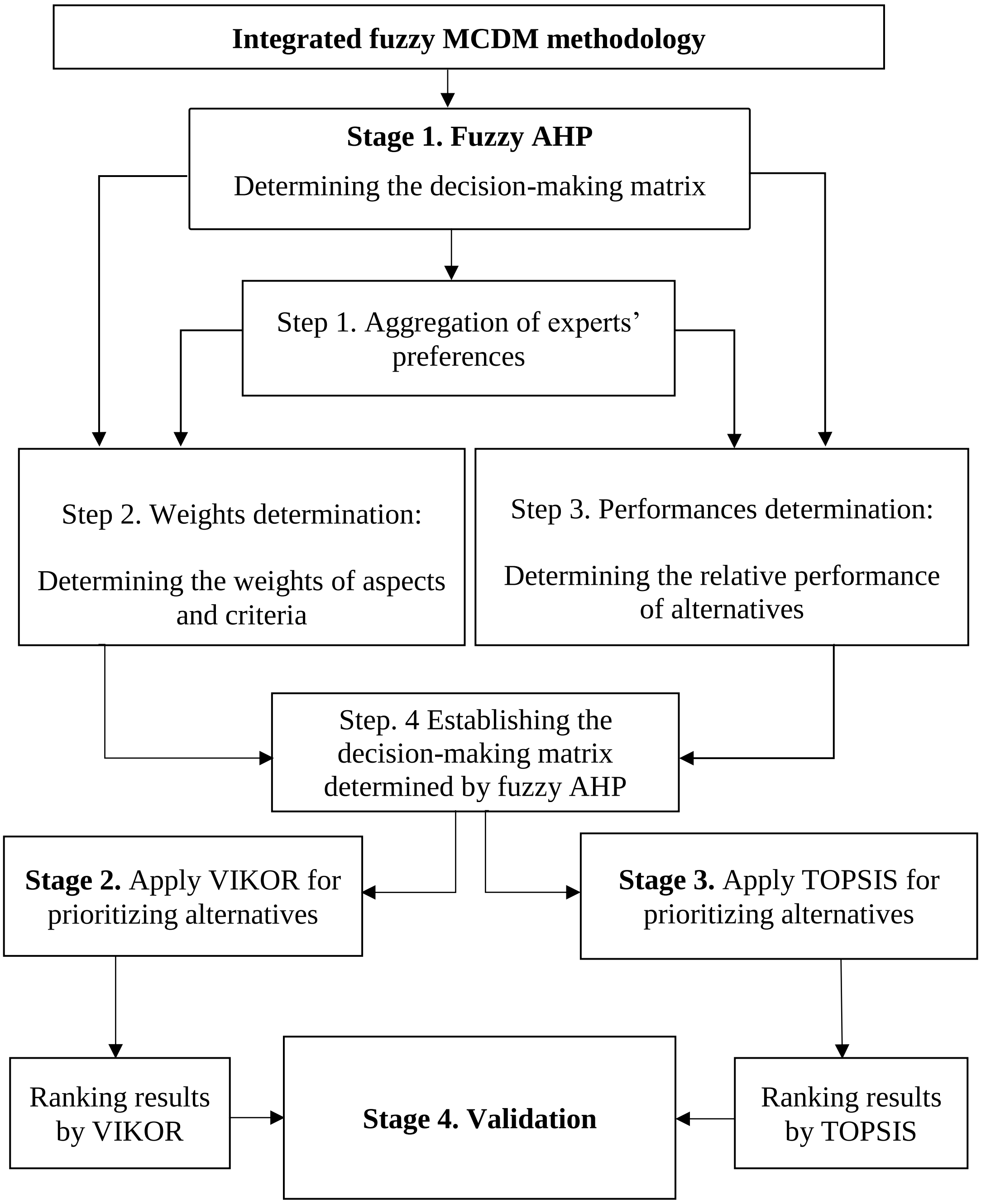
Figure 1. The proposed MCDM for the evaluation criterion system



3.2 The propose integrated fuzzy MCDM methodology

The intergraded fuzzy MCDM approach proposed in part (2) of the MCDM framework is employed to prioritize technological alternatives towards the set goal. Some of the data of the alternatives with regard to some of the criteria are not crisp values or cannot be represented quantitatively. To overcome these shortcomings, fuzzy AHP was used to determine not only the weight of each criterion, which represents its relative importance of the evaluation criteria in the decision-making, but also the relative performance of alternatives for emissions reduction with respect to each criterion. In fuzzy AHP, such a term is represented by a fuzzy set that consists of two components, a set of elements *x* and an associated membership function *u(x)* (Zimmermann, 2011). The fuzzy AHP technique is widely employed to determine the weights of criteria and the relative importance of alternatives in a structured way based on a pairwise comparison when subjective judgments may be inaccurate and uncertain (Celik & Akyuz, 2018; Ecer, 2020). While using the fuzzy-AHP method, experts' linguistic preferences (e.g., ‘equal importance’, ‘moderately importance’, and ‘more importance’) are mapped with fuzzy numbers, for example trapezoidal fuzzy number and (TraFN) Triangular fuzzy number (TFN), to decide the preferences and importance of one criterion over another. Subsequently, TOPSIS and VIKOR techniques are applied to rank the alternative technologies based on their overall performance. The proposed fuzzy integrated MCDM approach consists of four stages, as shown in Figure 2. It will be discussed in detail in this chapter.

Figure 2. The proposed integrated fuzzy MCDM methodology



The four the stages of the proposed integrated fuzzy MCDM approach are presented in the following steps;

3.2.1 Fuzzy AHP for determining the decision-making matrix

According to Liu et al., (2020), the fuzzy AHP method includes the following steps;

Given any real number k and two fuzzy triangular numbers $\tilde{A}_1 = (l_1, m_1, u_1)$ and $\tilde{A}_2 = (l_2, m_2, u_2)$, the basic fuzzy arithmetic operations are summarised (Lima et al., 2014); as shown in Eq. (1).

$$\begin{aligned}
\tilde{A}_1 \oplus \tilde{A}_2 &= (l_1 + l_2, m_1 + m_2, u_1 + u_2) \\
\tilde{A}_1 \ominus \tilde{A}_2 &= (l_1 - l_2, m_1 - m_2, u_1 - u_2) \\
\tilde{A}_1 \oslash \tilde{A}_2 &= (l_1/l_2, m_1/m_2, u_1/u_2) \qquad (1) \\
\tilde{A}_1 \otimes \tilde{A}_2 &= (l_1.l_2, m_1.m_2, u_1.u_2) \\
k \otimes \tilde{A}_2 &= (k.l_2, k.m_2, k.u_2) \\
\text{Inverse } (\tilde{A}_1) &= (l_1, m_1, u_1)^{-1} \approx (1/u_1, 1/m_1, 1/l_1)
\end{aligned}$$

3.2.1.1 Aggregation of experts' preferences

One challenge of using subjective values is that the opinions of different decision-makers or experts could differ. Their preferences need to be aggregated into an overall preference relation that can be used as a foundation for pairwise comparison to generate a concluding result for ranking alternatives (Beliakov et al., 2015). Geometric mean (Zimmer et al., 2017) and arithmetic mean (Ahmet Kilic, 2019) are two different mean methods used to deduct the average among experts' judgements. The arithmetic mean is chosen because it is easy, involving only arithmetic addition and division, which is described as follows:

Let (*DM₁, DM₂… DMq)* be the q experts and (*C₁, C₂… Cn)* be the n performance criteria and Let $\tilde{C}_{ij}{}^{(t)} = (l_{ij}{}^{(t)}, m_{ij}{}^{(t)}, u_{ij}{}^{(t)})$ be a TFN representing the relative importance C_i over C_j evaluated by DM_t. The average aggregated relative importance $\tilde{C}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ for C_i over C_j can be calculated using Eq. (2).

$$\tilde{C}_{ij} = \frac{1}{q}\sum_{t=1}^{q} \tilde{C}_{ij}{}^{(t)}$$

Or, (2)

$$\tilde{C}_{ij} = \frac{1}{q} \otimes (\tilde{C}_{ij}{}^{1} \oplus \tilde{C}_{ij2}{}^{2} \oplus \ldots . \oplus \tilde{C}_{ij}{}^{q})$$

Where

$$l_{ij} = \frac{1}{q}\sum_{t=1}^{q} l_{ij}{}^{(t)}, m_{ij} = \frac{1}{q}\sum_{t=1}^{q} m_{ij}{}^{(t)}, u_{ij} = \frac{1}{q}\sum_{t=1}^{q} u_{ij}{}^{(t)}$$

$$Where\ t = 1,2 \ldots \ldots q; i,j = 1,2 \ldots \ldots n$$

3.2.1.2 Weights importance determination

Researchers apply two dominant defuzzification methods, namely the centroid method (Ross, 2004) and the extent analysis method (Chang, 1996b), which are used to calculate weights/priorities and translate TFNs into crisp values in the fuzzy pairwise comparison matrix. In this study, the extent analysis method (EAM) is chosen for the simplicity of its arithmetic operations but having the following few steps.

3.2.1.3 Determination of the value of the fuzzy synthetic extent with respect to each attribute (criterion/ factor)

Let $F = [\tilde{C}_{ij}]_{n\times n}$ be a fuzzy pairwise comparison matrix, calculating the value of the fuzzy synthetic extent with respect to each criterion/factor can be represented by the fuzzy weight ($\widetilde{W}_i$) of element i, which can be determined according to Eq. (3).

$$\widetilde{W}_i = \sum_{j=1}^{m} \tilde{C}_{ij} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} \tilde{C}_{ij}\right]^{-1} \qquad (3)$$

Where

$$\sum_{j=1}^{m} \tilde{C}_{ij} = \left(\sum_{j=1}^{m} \tilde{C}_{ijl}, \sum_{j=1}^{m} \tilde{C}_{ijm}, \sum_{j=1}^{m} \tilde{C}_{iju}\right), j = 1,2,3 \ldots\ldots, m \text{ and } i = 1,2, \ldots\ldots n$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} \tilde{C}_{ij}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} \tilde{C}_{iju}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} \tilde{C}_{ijm}}, \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{m} \tilde{C}_{ijl}}\right)$$

3.2.1.4 Calculating the degree of possibility

The crisp weight of i is determined as the minimum degree of possibility that its fuzzy weight ($\widetilde{W}_i$) is greater than the fuzzy weight of the others. Considering two TFNs as presented by Eq. (4) and illustrated in figure 3.

$$\tilde{A}_1 = (l_1, m_1, u_1) \quad ; \tilde{A}_2 = (l_2, m_2, u_2) \qquad (4)$$

The degree of possibility of $\tilde{A}_2 \geq \tilde{A}_1$ can be determined using Eq. (5).

$$V(\tilde{A}_2 \geq \tilde{A}_1) = \sup_{y \geq x}[min(u_{\tilde{A}_1(x)}, u_{\tilde{A}_2(y)})] = hgt\,(\tilde{A}_1 \cap \tilde{A}_2) = u_{\tilde{A}_2(d)}$$

$$\begin{cases} 1, \ if\ m_2 \geq m_1 \\ 0, \ \ l_1 \geq u_2 \\ \frac{(l_1 - u_2)}{(m_2 - u_2) - (m_1 - l_1)}, \ otherwise \end{cases} \qquad (5)$$

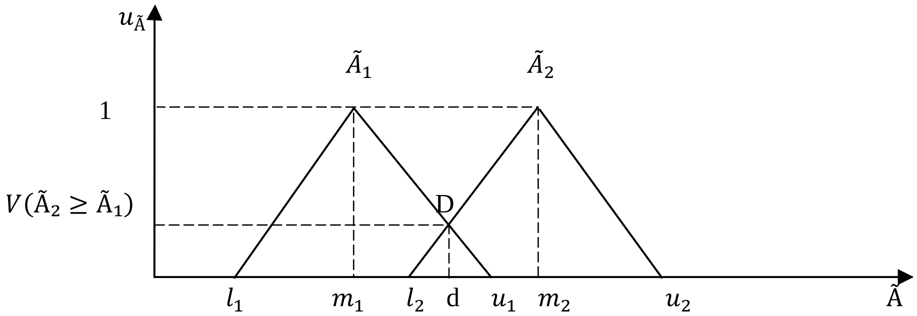


Figure 3. Fuzzy Triangular Numbers $\tilde{A}_1$ and $\tilde{A}_2$

3.2.1.5 Local weight determination

The crisp weight of i (w_i) is then calculated by Eq. (6).

$$w_i = V\left(\tilde{A}_i \geq \tilde{A}_1, \tilde{A}_2, \dots, \tilde{A}_n\right) = V\left[\left(\tilde{A}_i \geq \tilde{A}_1\right) and \left(\tilde{A}_i \geq \tilde{A}_2\right) and \dots. and \left(\tilde{A}_i \geq \tilde{A}_n\right)\right] = min\, V\left(\tilde{A}_i \geq \tilde{A}_k\right),\ k = 1,2,3 \dots n\ and\ k \neq i \tag{6}$$

The local weight (the weight vector of the *n* criteria/factors) is defined by Eq. (7).

$$w_i = (w_1, w_2, \dots., w_n)\ ,\ \ i = 1,2 \dots n \tag{7}$$

3.2.1.6 Normalized weight determination

The normalised weight vector is calculated by Eq.s,(8; 9).

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i},\quad i = 1,2 \dots n \tag{8}$$

$$W_i = (w_1, w_2, \dots w_n) \tag{9}$$

Fuzzy AHP is first used for determining the weights of each aspect and that of the criterion in each aspect; subsequently, the global weight of each criterion can be obtained by calculating the product of the weight of each criterion and the weight of the aspect to which this criterion belongs. Thus, the global weight of each criterion is determined by Eq. (10).

$$W_{iglobal} = \left(W_{iaspect} \times W_{icreteria}\right)\qquad ,\ i = 1,2, \dots \dots n \tag{10}$$

3.2.1.7 Relative performances determination

The relative performance of alternatives with regard to each criterion are determined according to the previous steps of Fuzzy AHP.

3.2.1.8 Establish the decision-making matrix determined by fuzzy AHP

The decision decision-making matrix with m alternatives and n criteria is represented as $X = (x_{ij})_{m \times n}$ and be the data of the j-th criterion with respect to the i-th alternative and w_j be the weight of the j-th criterion, which are determined by the fuzzy AHP. In fact, all data reflecting the values of the alternative technologies with respect to each criterion can be considered as normalized data as they are determined based on their relative priorities by the fuzzy AHP (Ren & Lützen, 2015b). Thus, after establishing the decision-making matrix, the VIKOR and TOPSIS techniques are applied to prioritize the technological alternatives and provide a preliminary sequence to the decision-makers for the set goal (G).

3.2.2 Apply VIKOR technique for prioritizing alternatives

The VIKOR approach consists of the following steps (Więckowski' & Sałabun, 2020; Kim & Ahn, 2019);

Let it be assumed that a decision decision-making matrix with m alternatives and n criteria is represented as $X = (x_{ij})_{m \times n}$ and be the data of the j-th criterion with respect to the i-th alternative and w_j be the weight of the j-th criterion, which can be determined by fuzzy AHP.

3.2.2.1 Criteria normalisation

The data of the alternatives with regard to the cost criteria and the beneficial criteria can be normalized using Eqs. (11; 12), respectively; consequently, the cost criteria can be transformed into a set of beneficial criteria.

$$f_{ij} = \frac{x_{ij} - d_j}{D_j - d_j} \tag{11}$$

$$f_{ij} = \frac{D_j - x_{ij}}{D_j - d_j} \tag{12}$$

Where

$$D_j = max_i\left(x_{ij}\right),\ and\ \ d_j = min_i\left(x_{ij}\right);i = 1,2\ldots,m\,;j = 1,2\ldots,n$$

3.2.2.2 Determining the L_P metric

Defining the L_p-metric as represented by Eq. (13)

$$L_{p,i} = \left\{\sum_{j=1}^{n}\left[\frac{w_j(f_j^*-f_{ij})}{(f_j^*-f_j^-)}\right]^p\right\}^{\frac{1}{p}},1\leq p \leq \infty;\quad for\ i = 1,2,\ldots\ldots,m \tag{13}$$

Where w_j represents the weight of the j-th criterion, and the best f_j^* and worst f_j^- values of the j-th criterion. If the j-th function represents a benefit f_j^* and f_j^- are represented by Eq. (14)

$$f_j^* = max\left(x_{ij}\right),\quad f_j^- = min\, f_{ij};\ \ j\ = 1.2.\ldots.m \tag{14}$$

3.2.2.3 Calculate the values of S_i and R_i

Calculate the values S_i and R_i by Eqs. (15; 16), respectively.

$$S_i = \sum_{j=1}^{n}\frac{w_j(f_j^*-f_{ij})}{(f_j^*-f_j^-)} = L_{p=1,i};\ for\ i\ = 1.2.\ldots.m \tag{15}$$

$$R_i = max_j\frac{w_j(f_j^*-f_{ij})}{(f_j^*-f_j^-)} = L_{p=\infty,j};\ for\ i\ = 1.2.\ldots.m \tag{16}$$

The values of S_i and R_i are included to develop the ranking measurements in the VIKOR method. The solutions obtained by min S_i and min R_i have a maximum group utility (“majority” rule) and a minimum of the individual regret of the “opponent”, respectively.

3.2.2.4 Calculate the values of Q_i

Q_i values can be determined by using Eq. (17).

Factor (v) is introduced as the weight of the strategy of 'the majority of attributes', which could take a value of [0 1] and is generally taken as 0.5.

$$Q_i = \mathrm{v}\frac{(S_i - S^*)}{(S^- - S^*)} + (1 - \mathrm{v})\frac{(R_i - R^*)}{(R^- - R^*)},\ i = 1,2, \ldots .m \tag{17}$$

Where

$S^* = min\ S_i$; $S^- = max\ S_i$; $R^* = min\ R_i$; $R^- = max\ R_i$ and $\mathrm{v} = 0{,}5$

3.2.2.5 Ranking of the alternatives based on the values Q_i, S_i, and R_i

Rank alternatives, sorting by the minimum values of Q_i, S_i, and R_i, in descending order. Note that the greater the values of Q_i, S_i, or R_i, the less superior the corresponding alternative will be, which result is three ranking lists (RLs).

3.2.2.6 Suggest a compromise solution or set of compromise solutions according to the three ranking lists (RLs)

Suggest the compromise solution or set of compromise solutions by using the three ranking lists (RLs) according to the values of Q_i, S_i, and R_i. The alternative $A^{(1)}$ is ranked as the best solution by the measure Q_i (minimum) if the following two conditions can be satisfied:

C_1 - Acceptable advantage:

$$Q(A^{(2)}) - Q(A^{(1)}) \geq DQ \tag{18}$$

Where

$A^{(2)}$ is the alternative with second the position in the ranking list by Q_i;

$DQ = 1/(m-1)$; m is the number of alternatives.

C_2 - Acceptable stability in decision making:

Alternative $A^{(1)}$ must also be ranked as the best by S_i and/or R_i. This compromise solution is stable within a decision-making process, which could be "voting by majority rule" (when $v > 0.5$ is needed), or "by consensus" $v \approx 0.5$, or "with veto" ($v < 0.5$).

If one of the conditions is not met, the set of compromise solutions is suggested as follows:

1- If **C_1** is satisfied and **C_2** is not satisfied, then both scenarios $A^{(1)}$ and $A^{(2)}$ are proposed as the best solutions.

2- If **C_1** is not satisfied, then a set of scenarios $A^{(1)}, A^{(2)}, \ldots, A^{(M)}$ is proposed as the best choices, where $A^{(M)}$ is defined by Eq. (19) for maximum M (the positions of these alternatives are 'in closeness').

$$Q(A^{(M)}) - Q(A^{(1)}) < DQ \tag{19}$$

3.2.3 Apply TOPSIS technique to prioritize the alternatives

According to Dymova et al., (2021), the TOPSIS method includes the followings steps;

We assume that we have the decision decision-making matrix with m alternatives and n criteria, is represented as $X = (x_{ij})_{m \times n}$ and let be the data of the j-th criterion with respect to the i-th alternative and w_j be the weight of the j-th criterion, which can be determined by fuzzy AHP.

3.2.3.1 Determination of the normalized decision matrix

The normalized values (r_{ij}) are calculated according to Eq. (20) for profit criteria and Eq. (21) for cost criteria as follows:

$$r_{ij} = \frac{x_{ij} - min_i(x_{ij})}{max_i(x_{ij}) - min_i(x_{ij})}; \ \ i = 1,2 \ldots.,m \ ; \ \ j = 1,2 \ldots,n \tag{20}$$

$$r_{ij} = \frac{max_i(x_{ij}) - x_{ij}}{max_i(x_{ij}) - min_i(x_{ij})} \ ; \ i = 1,2 \ldots.,m \ ; \ \ j = 1,2 \ldots,n \tag{21}$$

3.2.3.2 Determination of the weighted normalized decision matrix

Calculate the weighted normalized decision matrix by computing the values of V_{ij} according to Eq. (22).

$$V_{ij} = w_j r_{ij} \ ; \ i = 1,2 \ldots.,m \ ; \ \ j = 1,2 \ldots,n \tag{22}$$

3.2.3.3 Determination of the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS)

PIS is defined as maximum values for each criterion Eq. (23) and NIS as minimum values for each criterion Eq. (24).

$$V_j^{\,*} = \{V_1^{\,*}, V_2^{\,*}, \ldots.., V_n^{\,*}\} = \{max_i(V_{ij})\} \ ; \ i = 1,2 \ldots.,m \ ; \ \ j = 1,2 \ldots,n \tag{23}$$

$$V_j^{\,-} = \{V_1^{\,-}, V_2^{\,-}, \ldots.., V_n^{\,-}\} = \{min_i(V_{ij})\}; \ \ i = 1,2 \ldots.,m \ ; \ j = 1,2 \ldots,n \tag{24}$$

3.2.3.4 Calculate the distance from PIS and NIS for each alternative

Calculate distance from PIS and NIS for each alternative using Eqs. (25; 26).

$$D_i^{\ *} = \sqrt{\sum_{J=1}^{n}(V_{ij} - V_j^{\ *})^2} \ ; i \ = 1,2 \ldots.,m \tag{25}$$

$$D_i^{\ -} = \sqrt{\sum_{J=1}^{n}(V_{ij} - V_j^{\ -})^2} \ ; \ i = 1,2 \ldots.,m \tag{26}$$

3.2.3.5 Calculate score (*P*$_i$*) of each alternative

Calculate the score (P_i*) of each alternative using Eq. (27).

$$P_i^{\ *} = \frac{D_i^{\ -}}{D_i^{\ -} + D_i^{\ *}} \ ; \ ; \ i = 1,2 \ldots.,m \tag{27}$$

Where $0 \leq Pi* \leq 1$

3.2.3.6 Rank the alternative according to the score (*P*$_i$*) of each alternative

A set of alternatives can now be sorted by preference based on descending order of the value of P_i*. The higher the value of the index, the better the performance of the alternative.

$$\begin{cases} P_i^{\ *} = 1 \text{ only if the alternative solution presents the best conditions;} \\ P_i^{\ *} = 0 \text{ if and only if the alternative solution presents the worst conditions.} \end{cases}$$

3.2.4 Validation

At this stage, the results (ranking lists) of the two applied ranking methods (VIKOR and TOPSIS) can be analysed and compared to conclude on the best suitable solutions for emissions reduction from shipping. Afterwards, sensitivity analysis will be performed using the afore-mentioned ranking techniques to validate the robustness of the results.

Chapter 4. Case study

To illustrate the proposed MCDM framework, five feasible alternative technologies, such as LSFOs (A_1); Scrubbers (A_2); LNG (A_3); Methanol (A_4); and Ammonia (A_5), are preselected and analysed for regulatory compliance for emissions reduction from shipping. In addition, nineteen (19) criteria under five (5) factors are considered, as presented in Table 1. Decision criteria can be classified into two opposing categories: "benefit" and "cost" criteria. The benefit criteria can be named “reward” criteria and cost criteria, “regret” or “loss” criteria. In contrast to cost criteria, a benefit criterion means that the higher an alternative score in terms of it, the better the alternative is (Triantaphyllou & Baig, 2005); as shown in Table 1.

Table 1. The criteria for evaluating the sustainability of low-emission technologies.

Factors (Aspects)	Sub-factors (Criteria)	Abbreviation	Category
Technical (TC)	Energy efficiency	T_1	Beneficial
	Technology reliability	T_2	Beneficial
	Safety	T_3	Beneficial
	Maturity	T_4	Beneficial
Economic (EC)	Margin profit	EC_1	Beneficial
	Operational Cost	EC_2	Cost
	Capital Cost	EC_3	Cost
	Life cycle Cost	EC_4	Cost
Environmental (EN)	Impact on SO_X emissions reduction	EN_1	Beneficial
	Impact on NO_X emissions reduction	EN_2	Beneficial
	Impact on BC emissions reduction	EN_3	Beneficial
	Impact on CH_4 emissions reduction	EN_4	Beneficial
	Impact on CO_2 emissions reduction	EN_5	Beneficial
Other-Factors (OP)	Ship age	F_1	Beneficial
	Ship size	F_2	Beneficial
	Primary trade Areas	F_3	Beneficial
	Sub-factor criteria	F_4	Beneficial
Social-Political (SP)	Government support	SP_1	Beneficial
	Externalities	SP_2	Cost

Semi-structured interviews were conducted to collect the data used as input for processing the proposed decision-making framework. This was achieved by undertaking interviews with various officials (decision-makers) of shipping companies in Sweden and Algeria. For instance, Mr. Jonas Moberg, Manager NB Projects Fleet at Gotland Tankers AB (Stockholm); Mr. Linus Edberg, Marine Manager at WISBY TANKERS AB (Gothenburg); and Mr. Benotmane Moustafa, Senior officer at Hyproc Shipping Company (Oran). Questionnaire forms representing pairwise comparisons for criteria/aspects and alternatives were prepared. These questionnaires allow interviewees to evaluate based on their preferences the importance weights of each selected attribute (aspects and criteria) and relative performance of each alternative technology with respect to each criterion, using fuzzy linguistic term sets. Accordingly, a “Likert scale” of fuzzy numbers ranging from 1 to 9 is used to translate linguistic expressions into triangular fuzzy numbers (Yazır, et al., 2021); as illustrated in Table 2.

Table 2. Linguistic scale and corresponding Triangular Fuzzy Numbers

Fuzzy number	Linguistic expressions	Membership function
$\tilde{A}_1$	Equally important	(1,1,1)
$\tilde{A}_2$	Moderately important	(1,1,3)
$\tilde{A}_3$	More important	(1,3,5)
$\tilde{A}_4$	Strongly important	(3,5,7)
$\tilde{A}_5$	Very strongly important	(5,7,9)
$\tilde{A}_6$	Extremely important	(7,9,9)

4.1 Fuzzy AHP for determining the decision-making matrix

4.1.1 Aggregation of experts’ preferences

Based on the pairwise comparison, decision-makers were asked to assign the weight of one aspect over another aspect. The results are presented in Table 3. The data were transformed into triangular fuzzy numbers, as shown in Table 4.

Table 3. Decision makers´ preferences towards aspects.

Aspect	Decision makers	TC	EC	EN	SP	OF
TC	DM_1	EI	MOI	MOI	MOI	MOI
	DM_2	EI	EI	EI	MI	MOI
	DM_3	EI	MI	EI	EI	EI
EC	DM_1		EI	MI	MOI	MOI
	DM_2		EI	EI	EI	EI
	DM_3		EI	EI	EI	EI
EN	DM_1			EI	SI	MOI
	DM_2			EI	MOI	MI
	DM_3			EI	EI	EI
SP	DM_1				EI	MOI
	DM_2				EI	EI
	DM_3				EI	MI
OF	DM_1					EI
	DM_2					EI
	DM_3					EI

Table 4. Translating decision makers´ preferences towards aspects into fuzzy triangular numbers.

Aspect	Decision makers	TC	EC	EN	SP	OF
TC	DM$_1$	(1,1,1)	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)
	DM$_2$	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,3)	(1,3,5)
	DM$_3$	(1,1,1)	(1,1,3)	(1,1,1)	(1,1,1)	(1,1,1)
EC	DM$_1$		(1,1,1)	(1,1,3)	(1,3,5)	(1,3,5)
	DM$_2$		(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
	DM$_3$		(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
EN	DM$_1$			(1,1,1)	(3,5,7)	(1,3,5)
	DM$_2$			(1,1,1)	(1,3,5)	(1,1,3)
	DM$_3$			(1,1,1)	(1,1,1)	(1,1,1)
SP	DM$_1$				(1,1,1)	(1,3,5)
	DM$_2$				(1,1,1)	(1,1,1)
	DM$_3$				(1,1,1)	(1,1,3)
OF	DM$_1$					(1,1,1)
	DM$_2$					(1,1,1)
	DM$_3$					(1,1,1)

The figures are completed in Table 4, using the corresponding fuzzy reciprocal data (fuzzy numbers) expressing the fuzzy reciprocal linguistic preferences; determined according to Eq. (1). Afterwards, the aggregation of experts' preferences is performed using the Eq. (2). As a result, the aggregated fuzzy comparison matrix determining the priority weights of five aspects is defined, as shown in Table 5.

Table 5. Represents aggregated fuzzy comparison matrix of aspects

Asp	TC	EC	EN	SP	OP
TC	(1, 1, 1)	(1, 1.67, 3)	(1, 1.67, 2.33)	(1, 1.67, 3)	(1, 2.33, 3.67)
EC	(0.51, 0.78, 1)	(1, 1, 1)	(1, 1, 1.67)	(1, 1.67, 2.33)	(1, 1.67, 2.33)
EN	(0.73, 0.77, 1)	(0,77, 1, 1)	(1, 1, 1)	(1.66, 3, 4.33)	(1, 1.66, 3)
SP	(0.51, 0.77, 1)	(0.73, 077, 1)	(0.44, 0.51, 0.77)	(1, 1, 1)	(1, 1. 66, 3)
OF	(0.46, 0.55, 1)	(0.73, 0.77, 1)	(0.51, 0.77, 1)	(0.51, 0.77, 1)	(1, 1, 1)

4.1.2 Fuzzy synthetic extent calculation

Considering data from the aggregated fuzzy comparison matrix from Table 6 (above for aspects); the Eq. (3) can be used for calculation of values of fuzzy synthetic extent of five aspects with regard to the set goal as follows:

$$\widetilde{W}_{TC} = (5,\ 8.33,\ 13) \otimes (21.60,\ 30.51,\ 43.44)^{-1} = (5,\ 8.33,\ 13) \otimes \left(\frac{1}{43.44}, \frac{1}{30.51}, \frac{1}{21.60}\right) = (0.1150,\ 0.2731,\ 0.6017)$$

$$\widetilde{W}_{EC} = (4.51,\ 6.11,\ 8.33) \otimes (21.60,\ 30.51\ ,\ 43.44)^{-1} = (4.51,\ 6.11,\ 8.33) \otimes \left(\frac{1}{43.44}, \frac{1}{30.51}, \frac{1}{21.60}\right) = (0.1038,\ 0.2002,\ 0.3857)$$

$$\widetilde{W}_{EN} = (5.17,\ 7.44,\ 10.33) \otimes (21.60,\ 30.51,\ 43.44)^{-1} = (5.17,\ 7.44,\ 10.33) \otimes \left(\frac{1}{43.44}, \frac{1}{30.51}, \frac{1}{21.60}\right) = (0.1191,\ 0.2439,\ 0.4783)$$

$$\widetilde{W}_{SP} = (3.69,\ 4.73,\ 6.77) \otimes (21.60,\ 30.51,\ 43.44)^{-1} = (3.69,\ 4.73,\ 6.77) \otimes \left(\frac{1}{43.44}, \frac{1}{30.51}, \frac{1}{21.60}\right) = (0.0849,\ 0.1551,\ 0.3137)$$

$$\widetilde{W}_{OF} = (3.22,\ 3.88,\ 5) \otimes (21.60,\ 30.51,\ 43.44)^{-1} = (3.22,\ 3.88,\ 5) \otimes \left(\frac{1}{43.44}, \frac{1}{30.51}, \frac{1}{21.60}\right) = (0.0741,\ 0.1274,\ 0.2314)$$

4.1.3 Comparison of fuzzy values

The possibility matrix can be determined. All elements, see Table 6, are calculated based on Eqs. (4; 5). Taking cell (2, 1) in this matrix as an example, the degree of possibility of $\widetilde{W}_{EC} \geq \widetilde{W}_{TC}$ can be calculated as follows:

$$V(\widetilde{W}_{EC} \geq \widetilde{W}_{TC}) = \frac{0.1150 - 03857}{(0.2002 - 0.3857) - (0.2731 - 0.1150)} = 0.79$$

Likewise, the other data of Table 6 are determined according to the same procedure.

Table 6. Possibility matrix for aspects

Aspects	TC	EC	EN	SP	OF	weight	Normalized weight
TC	/	1.00	1.00	1.00	1.00	1.00	0.264191
EC	0.79	/	0.86	1.00	1.00	0.79	0.208172
EN	0.93	1.00	/	1.00	1.00	0.93	0.244574
SP	0.63	0.82	0.69	/	1.00	0.63	0.165744
OF	0.44	0.64	0.49	0.84	/	0.44	0.117319

4.1.4 Local weight determination of aspects

The crisp weight (w_i) can be determined from data in Table 7 by using Eq. (6).

$$w_{EC} = \min V(\widetilde{W}_{EC} \geq \widetilde{W}_{TC}, \widetilde{W}_{EN}, \widetilde{W}_{SP}, \widetilde{W}_{OF}) = min(0.79, 0.86, 1, 1) = 0.79$$

Similarly, w_{TC} =1.0000, w_{EN}= 0.93, w_{SP} = 0.63, and $w_{OF} = 0.44$. Subsequently, the local weight (the weight vector) is defined by Eq. (7).

$$w_i = (1, 0.79, 0.93, 0.63, 0.44)$$

4.1.5 Normalized weight determination of aspects

Finally, the normalized weights of the five aspects can be determined using Eqs. (8; 9). As presented in Table 7.

W_i = (0.2641, 0.2081, 0.2445, 0.1657, 0.1173)

Table 7. Weights of aspects determined using fuzzy AHP

Aspects	Fuzzy weight			Local weight	Normalized weight
TC	0.11509	0.273126	0.601765	1.00	0.264190508
EC	0.103836	0.200292	0.385747	0.79	0.208171611
EN	0.119181	0.243992	0.478326	0.93	0.244574203
SP	0.084983	0.155134	0.31374	0.63	0.165744427
OF	0.074168	0.127457	0.231448	0.44	0.117319251

According to Table 7, the technical aspect emerges as an essential factor influencing the decision-making process for selecting the best technologies on-board ships for regulatory compliance, followed by environmental, economic, socio-political, and other-factors. These results are conceivable, logical, and plausible. The technologies used on board ships are crucial and the prerequisite for reducing emissions from seaborne transportation. The environmental aspect is the second factor considered by decision-makers given its importance in the decision-making process regarding the choice of technology on-board a ship, taking into account current and future environmental regulations (e.g., BC and SO_X emission controls). On the other hand, economic aspect should also be considered when selecting a compliant fuel option on-board a ship in line with profitability as a key element for the sustainability and growth of shipping companies. Although decision-makers do not prioritize socio-political factor over the above-mentioned factors, the support of the public and authorities in decision-making is essential to facilitate the adoption of low carbon alternative fuels on-board ships to meet IMO targets. This can be achieved through adequate incentives and the dissemination of up-to-date and necessary information to ship owners and operators on the latest developments in new alternative technologies. Finally, decision-makers consider other-factors (e.g., ship size, ship age, and primary trading area) less than the aforementioned aspects; notwithstanding, this aspect also has a significant role in decision making for selecting the best alternative technologies for emissions reduction from shipping, particularly when considering the issues of adaptability of engines and installation on-board small ships, the cost of investing in alternative technologies on-board old ships, and the availability of compliant alternative fuels in and beyond the primary trading area.

Following same method as discussed before and using the input data from the pairwise comparison for criteria in each aspect with regard to preferences of decision makers. The calculations are not given here since they follow the same method as discussed above. The weights of the criteria in each aspect can now be calculated, and the global weights of the criteria with respect to the set goal can be determined using Eq. (10).

Taking as example criterion for effect of energy efficiency (T_1), the global weight of T_1 = the weight of T_1 in technical aspect × the weight technical aspect, namely, $0.3397 \times 0.2641 = 0.0897$. Similarly, the global weights of the other criterion can be calculated and then normalized (See Table 8).

Table 8. Global weights of the criteria determined using fuzzy AHP

Criteria	Normalized weight	Global Weight	Normalized Global Weight
T_1	0.339780834	0.08976687	0.0897
T_2	0.284590343	0.07518607	0.0751
T_3	0.295475781	0.0780619	0.07806
T_4	0.080153042	0.02117567	0.0211
EC_1	0.340465558	0.07087526	0.07087
EC_2	0.325471837	0.067754	0.0677
EC_3	0.161352342	0.03358898	0.0335
EC_4	0.172710264	0.03595337	0.0359
EN_1	0.221770887	0.05423944	0.0542
EN_2	0.221770887	0.05423944	0.05423
EN_3	0.221770887	0.05423944	0.05423
EN_4	0,221770887	0.05423944	0.0542
EN_5	0.112916453	0.02761645	0.02761
F_1	0.25416907	0.02981892	0.0298
F_2	0.273676253	0.03210749	0.0321
F_3	0.301021463	0.03531561	0.0353
F_4	0.171133214	0.02007722	0.0200
SP_1	0.691782595	0.11465911	0.1146
SP_2	0.308217405	0.05108532	0.0510

The determination of the relative performances of alternative technologies for reducing shipping's emissions with respect to each criterion is performed using fuzzy AHP. Accordingly, the processing of decision makers' data preferences follows the same procedure described above with aspects. Thus, the decision-making matrix determined using fuzzy AHP for the criteria and relative performance of alternative technologies with regard to each criterion is presented in Table 9.

Table 9. Decision-making matrix determined using fuzzy AHP

Criteria	Normalized weight	A_1	A_2	A_3	A_4	A_5
T_1	0.0897	0.2367	0.2007	0.2182	0.2061	0.1381
T_2	0.0751	0.2750	0.1960	0.2178	0.1985	0.1124
T_3	0.07806	0.2898	0.2369	0.1907	0.1632	0.1192
T_4	0.0211	0.2775	0.2108	0.1895	0.1895	0.1324
EC_1	0.07087	0.2762	0.2047	0.1983	0.1886	0.1318
EC_2	0.0677	0.2639	0.2110	0.2061	0.1851	0.1337
EC_3	0.0335	0.2943	0.2788	0.0571	0.2105	0.1590
EC_4	0.0359	0.2632	0.2337	0.1943	0.1778	0.1307
EN_1	0.0542	0.3026	0.3248	0.1677	0.1005	0.1041
EN_2	0.05423	0.3213	0.3390	0.1482	0.0945	0.0967
EC_3	0.05423	0.3009	0.3589	0.1518	0.0929	0.0952
EC_4	0.0542	0.3281	0.1723	0.3945	0.0524	0.0524
EC_5	0.02761	0.2672	0.2519	0.2305	0.1218	0.1284
F_1	0.0298	0.2824	0.2661	0.1504	0.1504	0.1504
F_2	0.0321	0.3772	0.2170	0.1352	0.1352	0.1352
F_3	0.0353	0.3209	0.3077	0.2254	0.0729	0.0729
F_4	0.0200	0.3539	0.3347	0.1672	0.0731	0.0707
SP_1	0.1146	0.2647	0.2139	0.1901	0.1901	0.1410
SP_2	0.0510	0.3068	0.1879	0.1927	0.1927	0.1197

The decision matrix data determined using fuzzy AHP will be used for the pre-sequence of the prioritization of the selected alternatives for emissions reduction from shipping. All data representing the values of the five alternative technologies with respect to each criterion presented in Table 9, can be regarded as normalized data because they are determined according to their relative priorities by the fuzzy AHP. VIKOR and TOPSIS methods are employed to prioritize the alternative technologies.

4.2 Prioritization by VIKOR

Taking the data of decision-making matrix determined using fuzzy AHP, in Table 9. The best and the worst values of each criterion are determined using the Eq. (14). The first criterion-maturity (T_1) can be determined by: $min\{0.2367, 0.2007, 0.2182, 0.2061, 0.1381\} = 0.1381$;
$\max\{0.2367, 0.2007, 0.2182, 0.2061, 0.1381\} = 0.2367$.
Accordingly, the best and the worst values of the other criteria can also be determined as illustrated in Table 10.

Table 10. The best and worst values of each criterion

Criteria	f_j*	f_j^-
T_1	0,2367	0,1381
T_2	0,2750	0,1124
T_3	0,2898	0,1192
T_4	0,2775	0,1324
EC_1	0,2762	0,1318
EC_2	0,2639	0,1337
EC_3	0,2943	0,0571
EC_4	0,2632	0,1307
EN_1	0,3248	0,1005
EN_2	0,3390	0,0945
EN_3	0,3589	0,0929
EN_4	0,3945	0,0524
EN_5	0,2672	0,1218
F_1	0,2824	0,1504
F_2	0,3772	0,1352
F_3	0,3209	0,0729
F_4	0,3539	0,0707
SP_1	0,2647	0,1410
SP_2	0,3068	0,1197

Subsequently, the values of S_i and R_i with respect to the five alternatives can be calculated using Eqs. (15;16). Taking the values of S_i and R_i with respect to A_1 as an example.

$$\begin{aligned}
S_{A_1} = {} & \frac{0.0897(0.2367-0.2367)}{(0.2367-0{,}1381)} + \frac{0.07516(0.2750-0.2750)}{(0.2750-0.1124)} + \frac{0.0780(0.2898-0.2898)}{(0.2898-0.1192)} + \\
& \frac{0.0211(0.2775-0.2775)}{(0.2775-0{,}1324)} + \frac{0.0708(0.2762-0.2762)}{0.2762-0.1318} + \frac{0.0677(0.2639-0.2639)}{0.2639-0.1337} + \\
& \frac{0.0335(0.2943-0.2943)}{0.2943-0.0571} + \frac{0.0359(0{,}2632-0{,}2632)}{0.2632-0.1307} + \frac{0.05423(0{,}3248-0{,}3026)}{0.3248-0{,}1005} + \\
& \frac{0{,}05423(0{,}3390-0{,}3213)}{0.3390-0{,}0945} + \frac{0.0542(0.3589-0.3009)}{0.3589-0.0929} + \frac{0.0542(0.3945-0.3281)}{0.3945-0.0524} + \\
& \frac{0.0276(0.2672-0.2672)}{0.2672-0.1218} + \frac{0.0298(0.2824-0.2824)}{0.2824-0.1504} + \frac{0.0321(0.3772-0.3772)}{0.3772-0.1352} + \\
& \frac{0.0353(0.3209-0.3209)}{0.3209-0.0729} + \frac{0.0200(0.3539-0.3539)}{0.3539-0.0707} + \frac{0.1146(0.2647-0.2647)}{0.2647-0.1410} + \\
& \frac{0.0510(0.3068-0.3068)}{0.3068-0.1197} = 0{,}0316
\end{aligned}$$

$$\begin{aligned}
R_{A_1} = max \Bigg\{ & \frac{0.0897(0.2367-0.2367)}{(0.2367-0.1381)}, \frac{0.07516(0.2750-0.2750)}{(0.2750-0.1124)}, \\
& \frac{0.0780(0.2898-0.2898)}{(0.2898-0.1192)}, \frac{0.0211(0.2775-0.2775)}{(0.2775-0.1324)}, \frac{0.0708(0.2762-0.2762)}{0.2762-0.1318}, \\
& \frac{0.0677(0.2639-0.2639)}{0.2639-0.1337}, \frac{0.0335(0.2943-0.2943)}{0.2943-0.0571}, \frac{0.0359(0.2632-0.2632)}{0.2632-0.1307}, \\
& \frac{0.05423(0.3248-0.3026)}{0.3248-0.1005}, \frac{0.05423(0.3390-0.3213)}{0.3390-0.0945}, \frac{0.0542(0.3589-0.3009)}{0.3589-0.0929}, \\
& \frac{0.0542(0.3945-0.3281)}{0.3945-0.0524}, \frac{0{,}0276(0.2672-0.2672)}{0.2672-0.1218}, \frac{0.0298(0.2824-0.2824)}{0.2824-0.1504}, \\
& \frac{0.0321(0.3772-0{,}3772)}{0.3772-0.1352}, \frac{0.0353(0.3209-0.3209)}{0.3209-0.0729}, \frac{0.0200(0.3539-0.3539)}{0.3539-0.0707}, \\
& \frac{0.1146(0.2647-0.2647)}{0.2647-0.1410}, \frac{0.0510(0.3068-0.3068)}{0.3068-0.1197} \Bigg\} = 0.0118
\end{aligned}$$

Similarly, S_i and R_i with regard to A_2; A_3; A_4; and A_5, can also be determined, as presented in Table 11. Accordingly, we can deduct the values of S^*, S^-, R^* and R^- from Table 11 and we obtain as follows:

$$S^* = min\{0.0316, \ 0.3219, \ 0.5407, \ 0.7151, \ 0.9824\} = 0.0316$$

$$S^- = max\{0.0316, \ 0.3219, \ 0.5407, \ 0.7151, \ 0.9824\} = 0.9824$$

$$R^* = min\{0.0118, \ 0.0470, \ 0.0691, \ 0.0691, \ 0.1146\} = 0.0118$$

$$R^- = max\{0.0118, \ 0.0470, \ 0.0691, \ 0.0691, \ 0.1146\} = 0.1146$$

Table 11. The values of S_i and R_i of alternatives

Alternatives	S_i	R_i
A_1	0,0316	0,0118
A_2	0,3219	0,0470
A_3	0,5407	0,0691
A_4	0,7151	0,0691
A_5	0,9824	0,1146
S^*, R^*	0,0316	0,0118
S^-, R^-	0,9824	0,1146

Next, the values of Q_i with respect to the five alternatives under different conditions ($v = 0.1, 0.3, 0.5, 0.7, 0.9$) can be determined using Eq. (17). Taking the values of S_i and R_i with respect A_1 as an example, and when $v = 0.5$ the value of Q_1 with respect to A_1 is:

$$Q_{A_1} = 0,5\frac{(0.0316-0.0316)}{(0.9824-0.0316)} + (1-0,5)\frac{(0.0118-0.0118)}{0.1146-0.0118} = 0$$

Similarly, the other values of Q_i with regard to alternatives can also be calculated, as presented in Table 12.

Table 12. The ranks of the scenarios according to values of S_i, R_i, and Q_i based on the data determined using fuzzy AHP

Criteria or attribute	A_1	A_2	A_3	A_4	A_5
S_i	0,0316	0,3219	0,5407	0,7151	0,9824
R_i	0,0118	0,047	0,0691	0,0691	0,1146
Rank based S_i	1	2	3	4	5
Rank based R_i	1	2	3	4	5
$Q_i = (v = 0.1)$	0	0,3391	0,5555	0,5739	1
Rank based Q_i	1	2	3	4	5
$Q_i = (v = 0.3)$	0	0,3316	0,5510	0,6061	1
Rank based Q_i	1	2	3	4	5
$Q_i = (v = 0.5)$	0	0,3241	0,5466	0,6383	1
Rank based Q_i	1	2	3	4	5
$Q_i = (v = 0.7)$	0	0,3166	0,54214	0,6705	1
Rank based Q_i	1	2	3	4	5
$Q_i = (v = 0.9)$	0	0,3091	0,5376	0,7027	1
Rank based Q_i	1	2	3	4	5

Accordingly, the alternatives can be ranked based on the values Q_i , S_i , and R_i . The ranking lists determined by Q_i , S_i and R_i (under different v values) are obviously the same, and the prior sequence in the descending order is A_1 ; A_2 ; A_3; A_4; and A_5. Finally, the best solution can be determined. The condition 1 (**C_1**) can be checked using Eq. (18); for example, Q_i $(v = 0.5)$ we obtain results as follows:

0, 3241–0 > 0, 25; and condition 2 (**C_2**) is also satisfied as A_1 also be ranked as the best by *S* or/and *R.* Accordingly, condition 1 (**C_1**) and (**C_2**) are satisfied, as result, the compromise best solution is A_1. Therefore, LSFOs are ranked as the best solution for emissions reduction according to the data determined using fuzzy AHP.

For factor (v) of [0 1] same ranking results found for (Q_i); A_1 ranked first in the list by the VIKOR method and conditions (**C_1**) and (**C_2**) are fulfilled. Thus, the compromise best solution ranked by VIKOR is LSFOs.

4.3 Prioritization by TOPSIS

Taking the data of normalized decision-making matrix determined using fuzzy AHP as presented above in Table 9. We calculate the weighted normalized decision matrix by commuting the values (V_{ij}) according to Eq. (22).

Taking example of cell (1/1):

$$V_{11} = 0{,}089766871 \times 0{,}236757125 = 0{,}0212$$

We continue in the same way with other values (V_{ij}). The results as shown in Table 13.

Table 13. Weighted Normalized Decision Matrix

Criteria	A_1	A_2	A_3	A_4	A_5
T_1	0,0212	0,0180	0,0195	0,0185	0,0124
T_2	0,0206	0,0147	0,0163	0,0149	0,0084
T_3	0,0226	0,0184	0,0148	0,0127	0,0093
T_4	0,0058	0,0044	0,0040	0,0040	0,0028
EC_1	0,0195	0,0145	0,0140	0,0133	0,0093
EC_2	0,0178	0,0142	0,0139	0,0125	0,0090
EC_3	0,0098	0,0093	0,0019	0,0070	0,0053
EC_4	0,0094	0,0084	0,0069	0,0063	0,0047
EN_1	0,0164	0,0176	0,0090	0,0054	0,0056
EN_2	0,0174	0,0183	0,0080	0,0051	0,0052
EN_3	0,0163	0,0194	0,0082	0,0050	0,0051
EN_4	0,0177	0,0093	0,0214	0,0028	0,0028
EN_5	0,0073	0,0069	0,0063	0,0033	0,0035
F_1	0,0084	0,0079	0,0044	0,0044	0,0044
F_2	0,0121	0,0069	0,0043	0,0043	0,0043
F_3	0,0113	0,0108	0,0079	0,0025	0,0025
F_4	0,0071	0,0067	0,0033	0,0014	0,0014
SP_1	0,0303	0,0245	0,0217	0,0217	0,0161
SP_2	0,0156	0,0096	0,0098	0,0098	0,0061

Afterwards, Ideal best (V_j*) and Ideal worst (V_j^-) are determined using Eqs. (23; 24). The results as shown in the Table 14.

Table 14. The values of Ideal best (V_j*) and Ideal worst (V_j^-)

Criteria	V_j*	V_j^-
T_1	0,0212	0,0124
T_2	0,0206	0,0084
T_3	0,0226	0,0093
T_4	0,0058	0,0028
EC_1	0,0195	0,0093
EC_2	0,0178	0,0090
EC_3	0,0098	0,0019
EC_4	0,0094	0,0047
EN_1	0,0176	0,0054
EN_2	0,0183	0,0051
EN_3	0,0194	0,0050
EN_4	0,0214	0,0028
EN_5	0,0073	0,0033
F_1	0,0084	0,0044
F_2	0,0121	0,0043
F_3	0,0113	0,0025
F_4	0,0071	0,0014
SP_1	0,0303	0,0161
SP_2	0,0156	0,0061

Calculate distance from PIS and NIS for each alternative

Calculate the distance from PIS (D_i*) and NIS (D_i^-) for each alternative using the Eqs. (25; 26). The resulting will be used to calculate performance score (P_i*) of each alternative using Eq. (24). Afterwards, a set of alternatives can now be sorted by preference based on descending order of the value of P_i* determined by Eq. (24). As presented in table 15.

Table 15. The ranking of the alternatives based on descending order of the value of P_i*

Alternatives	D_i*	D_i^-	D_i*+D_i^-	P_i*	Rank
A_1	0,0050	0,0424	0,0474	0,8940	1
A_2	0,0186	0,0326	0,0513	0,6363	2
A_3	0,0267	0,0257	0,0524	0,4902	3
A_4	0,0375	0,0139	0,0515	0,2713	4
A_5	0,0446	0,0034	0,0481	0,0714	5

As shown in the results presented in the Table.16, A_1 presents the highest performance score (P_i*). Therefore, LSFOs is ranked the best alternative for emissions reduction from shipping by TOPSIS.

4.4 Validation

The results presented in Table 16 illustrate a similar ranking for the alternatives by VIKTOR and TOPSIS. In VIKOR, both conditions **C_1** and **C_2** are fulfilled. Thus, the best compromise solution for emissions reduction from seaborne transportation is low sulphur fuels.

Table 16. Comparison of VIKTOR vs TOPSIS ranking lists.

Alternatives	Rank-VIKOR (For v [0 1]; Qi, S_i and R_i)	Rank-TOPSIS (P_i*)
A1	1	1
A2	2	2
A3	3	3
A4	4	4
A5	5	5

Sensitivity analysis by varying the weights of the criteria is a relevant approach to investigate the robustness of the ranking results (Pham & 2019).

A sensitivity analysis was performed, using VIKOR and TOPSIS to prioritize the alternative measures for emissions reduction from shipping, to validate to the robustness of the results of this study by assigning different weights to the criteria by considering the following twenty cases.

Case (1): An equal weight of 0.052631579 was assigned to all criteria.

Cases (2–20): While the other criteria were given equal weight, a dominant weight was given to one criterion. For instance, an equal weight of 0.034 was assigned to the other 18 criteria in the case i (i=2, 3..., 20); on the other hand, a dominant weight of 0.388 was assigned to the (i-1)-th criterion. As an example of case 2, a weight of 0.034 was assigned to the other criteria, and a dominant weight of 0.388 was assigned to the first criterion (T_1), "Energy efficiency."

4.4.1 Sensitivity analysis using VIKOR

A sensitivity analysis was performed for the twenty cases by computing VIKOR under the proviso of "v = 0.5"

The values of Q_i, S_i, and R_i with regard to the five alternative technologies in the various cases are presented in Figure 4, Figure 5, and Figure 6. It can be observed that these values are sharply sensitive to the weights of the criteria. In addition, the compromise solutions under the terms of the aforementioned cases can also vary, as shown in Table 17. Consequently, the ranking of alternatives by VIKOR is very sensitive to the variation of the weights of the criteria.

Figure 4. Sensitivity analysis by changing the weights of criteria performed by VIKOR for cases (1-7)

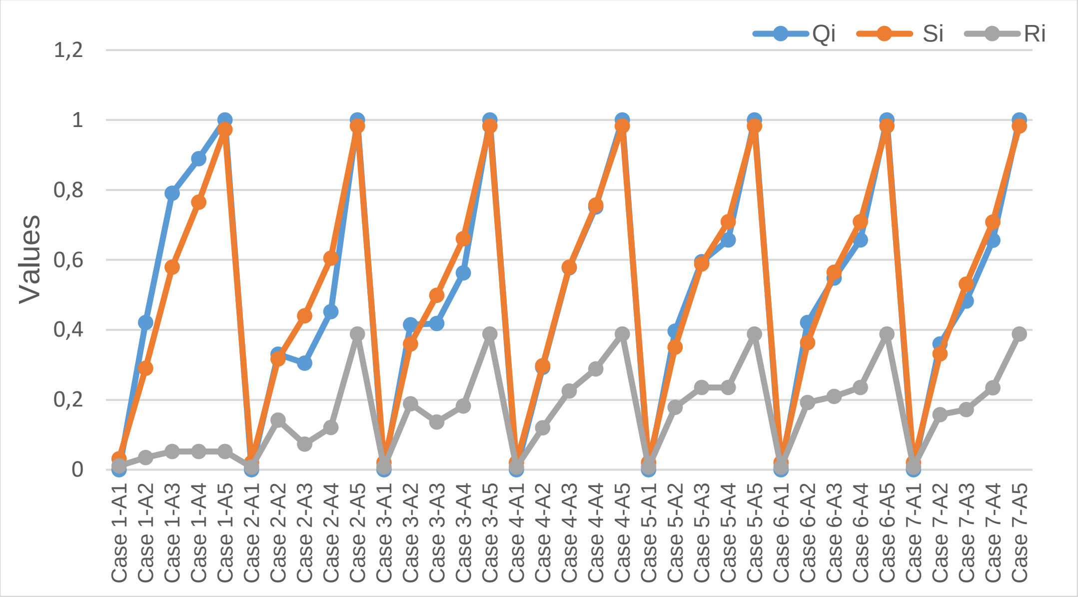


Figure 5. Sensitivity analysis by changing the weights of criteria performed by VIKOR for cases (8-14)

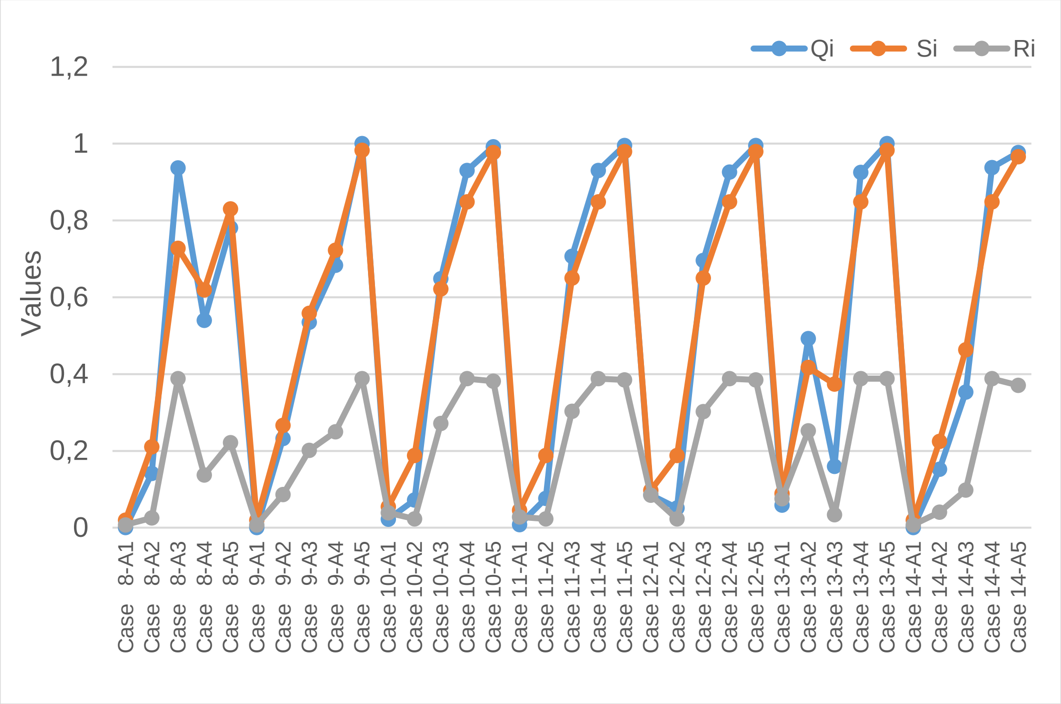


Figure 6. Sensitivity analysis by changing the weights of criteria performed by VIKOR for cases (15-20)

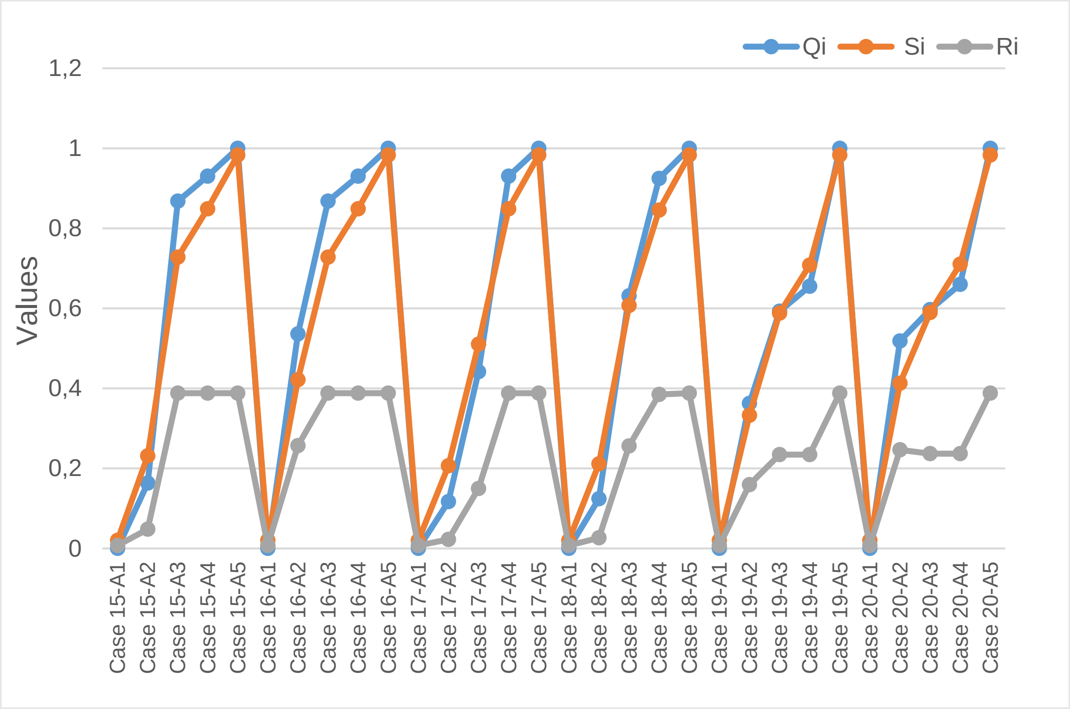


Table 17. The compromise solutions determined under the conditions of different cases by VIKOR

Cases	Compromise solutions
Case 1	A_1
Case 2	A_1, A_3
Case 3	A_1
Case 4	A_1
Case 5	A_1
Case 6	A_1
Case 7	A_1
Case 8	A_1, A_2
Case 9	A_1, A_2
Case 10	A_1, A_2
Case 11	A_1, A_2
Case 12	A_1, A_2
Case 13	A_1, A_3
Case 14	A_1, A_2
Case 15	A_1, A_2
Case 16	A_1
Case 17	A_1, A_2
Case 18	A_1, A_2
Case 19	A_1
Case 20	A_1

4.4.1 Sensitivity analysis using TOPSIS

A sensitivity analysis was conducted by assigning different weights to the criteria by studying the twenty cases mentioned above for running TOPSIS. The values of Pi^* with respect to these five alternatives in the different cases are presented in Figure 7. This figure shows that the value of $Pi*$ are highly sensitive to the weights of the criteria, which can affect the ranking of the alternatives. The ranking results determined in the different cases is represented in Table 18.

Figure 7. Sensitivity analysis by changing the weights of criteria performed by TOPSIS for different cases

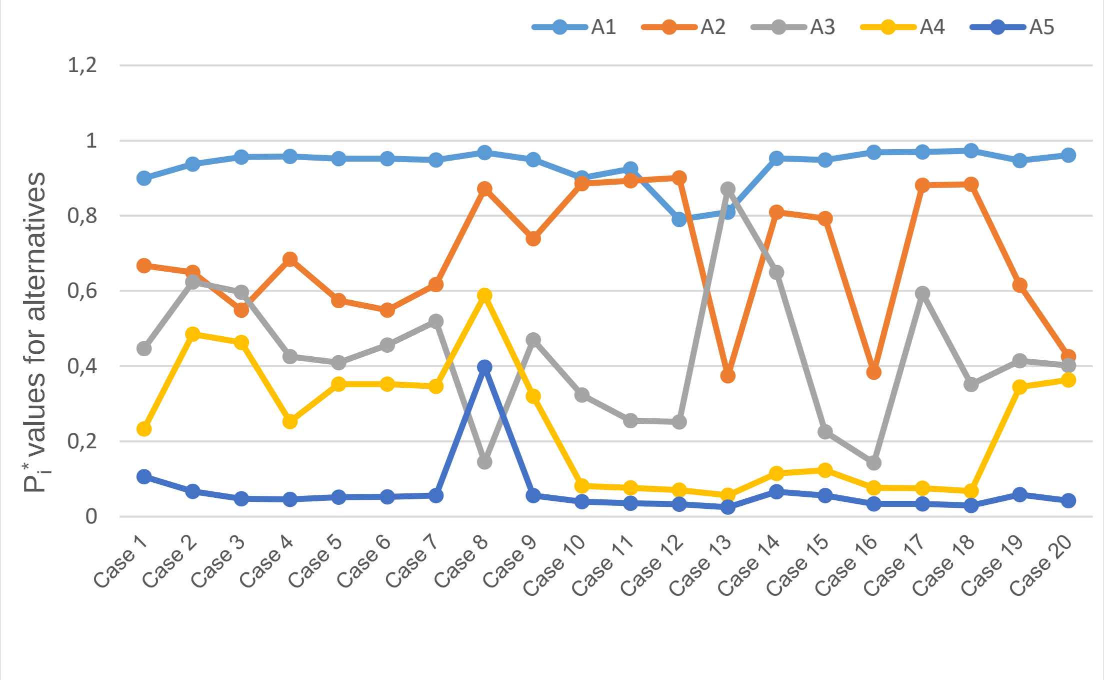


Table 18. The ranking of alternatives determined under the conditions of different cases by TOPSIS

Cases	A_1	A_2	A_3	A_4	A_5
Case 1	1	2	3	4	5
Case 2	1	2	3	4	5
Case 3	1	3	2	4	5
Case 4	1	2	3	4	5
Case 5	1	2	3	4	5
Case 6	1	2	3	4	5
Case 7	1	2	3	4	5
Case 8	1	2	5	3	4
Case 9	1	2	3	4	5
Case 10	1	2	3	4	5
Case 11	1	2	3	4	5
Case 12	2	1	3	4	5
Case 13	2	3	1	4	5
Case 14	1	2	3	4	5
Case 15	1	2	3	4	5
Case 16	1	2	3	4	5
Case 17	1	2	3	4	5
Case 18	1	2	3	4	5
Case 19	1	2	3	4	5
Case 20	1	2	3	4	5

It can be observed that the ranking of the alternatives is very sensitive to the weights of the criteria, as shown by the outcomes of the sensitivity analysis carried out when using VIKOR and TOPSIS to prioritize the alternative technologies for emissions reduction from shipping. This can reflect the relative importance of the criteria and the preferences of decision-makers in the decision making. Hence, determining the correct specific weights of the criteria in an appropriate manner that exactly matches the preferences of the decision-makers is a precondition for selecting the best alternative. For this reason, fuzzy AHP has been used to determine the weights of the criteria for sustainability evaluation of alternatives for regulatory compliance for emissions reduction from shipping.

Alternative LSFOs (A_1) is included in the compromise solutions for all the cases mentioned above when using VIKOR. Similarly, A_1 takes the lead in most cases when using TOPSIS, except for the cases 12 and 13, where scrubbers (A_2) and LNG (A_3) are ranked as the best measures for emissions reduction from shipping following respectively the dominant assigned weights for the criterion representing impact on the reduction of BC emissions (EN_3) and the criterion representing impact on the reduction of CH_4 emissions (EN_4). Indeed, the compromise solutions ranked by VIKOR in cases 12 and 13 are A_1, A_2 and A_1, A_3, respectively. These results are reasonable given the requirements to control BC and methane slip emissions from ships prior to the adoption of the alternatives A_2 and A_3 as compliant alternative fuels in accordance with new emissions regulations. Furthermore, the common top weights of criteria affecting the ranking of alternatives based on the sensitivity analysis performed when running VIKOR vs TOPSIS are EC_3, EN_3, and EN_4. Accordingly, the capital cost (EC_3) is also a determining criterion in the decision-making for the choice of an alternative technology on board a ship. In addition, it is apparent from Table 17 and Table 18 that the ranking of alternatives using VIKOR was affected by elven (11) criteria weights (e.g., T_1, EC_4, and EN_1) higher than TOPSIS, which was influenced only by four (4) criteria (e.g., T_2). Hence, the compromise solutions are highly sensitive to the weights of the criteria in VIKOR. Thus, VIKOR can lead to more accurate results than TOPSIS.

Chapter 5 Summary and conclusion

5.1 Summary

Due to the uncertainty surrounding fuel prices in the post-IMO-2020 and increasingly stringent environmental regulations, alternative technologies have become the top priority of numerous shipping companies looking for the best trade-off solutions, cost-effective energy-efficient options, for compliance. According to the results presented in the case study, energy efficiency is the most important criterion in decision-making regarding the choice of alternative fuels for regulatory compliance. In terms of environmental compliance, the reduction of SO_X, NO_X, BC and CH_4 emissions has been equally and importantly considered by decision-makers. However, the lack of sanctions and penalties lessens the concerns of decision-makers about CO_2 emissions. Although decision-makers less prioritize the socio-political factor over the other factors, government support is needed for the widespread and effective uptake of future low-carbon and zero-carbon fuels (e.g., hydrogen, fuel cells and batteries, and green ammonia…etc.) in the shipping industry to meet IMO ´emissions target.

LSFOs are ranked as the best compromise solution for emissions reduction from seaborne transportation as revealed by this case study, which is also consistent with the outcomes of some previous studies in the literature where LSFOs were considered as the best option in the short-term (Bui et al., 2020b; Bui & Perera, 2019c). These results reflect the issues of uncertainty and/or vagueness surrounding future low carbon alternative fuels within many shipping companies where financial factors strongly influence decision making, particularly in times of global crisis such as coronavirus pandemic. Although LSFOs are considered as the best compromise solution in the medium to long term for regulatory compliance, more attention should be paid by decision-makers (ship-owners and ship operators) to the latest research studies on low or zero-carbon fuels. Thus, decision makers can decide and invest in the best compliant fuel options based on their preferred interests while ensuring the sustainability of shipping companies and the global environment.

5.2 Conclusion

A holistic framework, a fuzzy MCDM approach, has been developed comprising nineteen criteria integrated into five aspects to assess and prioritize alternative technologies for regulatory frameworks. Five feasible alternative technologies, such as LSFOs; Scrubbers; LNG; Methanol; and Ammonia, were used to demonstrate the effectiveness of the proposed MCDM method. The output of this research study indicated that LSFOs is the best compromise solution for emissions reduction from seaborne transportation sequenced respectively by scrubbers, LNG, Methanol, and Ammonia.

In the proposed MCDM framework, fuzzy AHP was employed to determine the decision-making matrix, including the weights of the attributes (aspects/criteria) and the relative performance of alternatives with respect to each criterion, by involving different experts' opinions. The VIKOR and TOPSIS techniques were used to determine the concluding prioritization of alternatives. Afterwards, the ranking lists obtained using the VIKOR method and TOPSIS method were compared to conclude on the best alternative for regulatory compliance. As results, the ranking of the alternatives found to be similar for the two techniques in the case study. To validate the study results' robustness, sensitivity analysis was performed by varying the weights of criteria for running VIKOR and TOPSIS in 20 similar scenarios for each. This study revealed that the precision of the prioritization of alternatives is more sensitive to the weights of the criteria in VIKOR compared to TOPSIS.

All in all, the proposed framework has several advantages. For instance, to determine the weights of the criteria and relative performances of the alternatives with respect to each criterion, decision-makers are allowed to use linguistic terms to establish the comparison matrices. This framework does not require obtaining accurate data of the alternatives with respect to each criterion. It facilitates decision making under uncertainty and directly leads to the establishment of the normalized decision matrix in which the challenges encountered in the cost-benefit analysis have been overcome.

In addition, the suggested MCDM methodology helps to achieve rational and accurate alternative ranking results. This can be reached directly by comparing the results of two well-known techniques (VIKOR and TOPSIS) for ranking alternatives

Unlike advantages, inevitable drawbacks exist in the proposed method. For instance, all the data in the decision-making matrix is procured using fuzzy AHP. Although this technique can resolve the acute uncertainty in MCDM problems to select the most appropriate alternative technologies towards regulatory compliance, the final results will depend on the opinions and preferences of decision-makers following their up-to-date expertise, experience, and knowledge on the topic as the evaluation of attributes/alternatives carried out using subjectivity. In addition, some information that can be performed from literature, surveys, and statistics might be missing; for instance, some of the existing data, which can be represented by crisp numbers, were not used in the proposed MCDM method. Another disadvantage is that this form of scrutiny does not take into account the interrelationships among attributes; however, there are generally diverse correlations and interconnections among these attributes.

The proposed framework is a generic decision-making model for selecting the most sustainable technology. It can be effectively applied for regulatory compliance problems in the shipping industry and help decision-makers make the most rational decision under uncertainty and vagueness. Thus, the suggested model can also be used for similar regulatory compliance problems in other modes of transportation such as rail and road.

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Appendices

Appendix A. Questionnaire form to facilitate the pairwise comparison of the aspects with regards to goal, using linguistic terms

How important is aspect *Technical* when it is compared to aspect *Economic*?
How important is aspect *Technical* when it compared to aspect *Environmental*?
How important is aspect *Technical* when it is compared to aspect *Social-Political*?
How important is aspect *Technical* when it is compared to aspect *Other factors*?
How important is aspect *Economic* when it is compared to aspect *Environmental*?
How important is aspect *Economic* when it is compared to aspect *Social-Political*?
How important is aspect *Economic* when it is compared to aspect *Other factors*?
How important is aspect *Environmental* when it is compared to aspect *Social-Political*?
How important is aspect *Environmental* when it is compared to aspect *Other factors*?
How important is aspect *Social-Political* when it is compared to aspect *Other factors*?

Please select your choice by ticking (X)

Aspects	**Expert´s preference**						**Aspects**
	Comparison of aspects using linguistic terms						
	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	
Technical							Economic
Technical							Environmental
Technical							Social-Political
Technical							Other factors
Economic							Environmental
Economic							Social-Political
Economic							Other factors
Environmental							Social-Political
Environmental							Other factors
Social-Political							Other factors

Appendix B. Questionnaire form to facilitate the pairwise comparison of each criterion with respect to another criterion, using linguistic terms

How important is criterion *Energy efficiency* when it is compared to criterion *Technology reliability*?

How important is criterion *Energy efficiency* when it is compared to criterion *Safety*?

How important is criterion *Energy efficiency* when it is compared to criterion *Maturity*?

How important is criterion *Technology reliability* when it is compared to criterion *Safety*?

How important is criterion *Technology reliability* when it is compared to criterion *Maturity*?

How important is criterion *Safety* when it is compared to criterion *Maturity*?

Please select your choice by ticking (X)

Technical Criteria	**Expert´s preference**						**Technical Criteria**
	Comparison of criterion using linguistic terms						
Criterion	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Criterion**
Energy efficiency							Technology reliability
Energy efficiency							Safety
Energy efficiency							Maturity
Technology reliability							Safety
Technology reliability							Maturity
Safety							Maturity

How important is criterion *Margin profit* when it is compared to criterion *Operational cost*?

How important is criterion *Margin profit* when it is compared to criterion *Capital cost*?

How important is criterion *Margin profit* when it is compared to criterion *Life cycle cost*?

How important is criterion *Operational cost* when it is compared to criterion *Capital cost*?

How important is criterion *Operational cost* when it is compared to criterion *Life cycle cost*?

How important is criterion *Capital cost* when it is compared to criterion *Life cycle cost*?

Please select your choice by ticking (X)

Economic Criteria	**Expert´s preference**						**Economic Criteria**
	Comparison of criterion using linguistic terms						
Criterion	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Criterion**
Margin profit							Operational cost
Margin profit							Capital cost
Margin profit							Life cycle cost
Operational cost							Capital cost
Operational cost							Life cycle cost
Capital cost							Life cycle cost

How important is criterion *Impact on reduction of SOx emissions* when it is compared to criterion *Impact on the reduction of NOx emissions*?

How important is criterion *Impact on reduction of SOx emissions* when it is compared to criterion *Impact on reduction of BC emissions*?

How important is criterion *Impact on reduction of SOx emissions* when it is compared to criterion *Impact on the reduction of CH4 emissions*?

How important is criterion *Impact on reduction of SOx emissions* when it is compared to criterion *Impact on the reduction of the CO2 emissions*?

How important is criterion *Impact on the reduction of NOx emissions* when it is compared to criterion *Impact on the reduction of BC emissions*?

How important is criterion *Impact on the reduction of NOx emissions* when it is compared to criterion *Impact on the reduction of CH4 emissions*?

How important is criterion *Impact on the reduction of NOx emissions* when it is compared to criterion *Impact on the reduction of the CO2 emissions*?

How important is criterion *Impact on the reduction of BC emissions* when it is compared to criterion *Impact on the reduction of CH4 emissions*?

How important is criterion *Impact on the reduction of BC emissions* when it is compared to criterion *Impact on the reduction of the CO2 emissions*?

How important is criterion *Impact on the reduction of CH4 emissions* when it is compared to criterion *Impact on the reduction of the CO2 emissions*?

Please select your choice by ticking (X)

Environmental Criteria **Criterion**	**Expert´s preference**						**Environmental Criteria** **Criterion**
	Comparison of criterion using linguistic terms						
	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	
Impact on the reduction of SOx emissions							Impact on the reduction of NOx emissions
Impact on the reduction of SOx emissions							Impact on the reduction of BC emissions
Impact on the reduction of SOx emissions							Impact on the reduction of CH4 emissions
Impact on the reduction of SOx emissions							Impact on the reduction of the CO2 emissions
Impact on the reduction of NOx emissions							Impact on the reduction BC emissions
Impact on the reduction of NOx emissions							Impact on the reduction of CH4 emissions
Impact on the reduction of NOx emissions							Impact on the reduction of the CO2 emissions
Impact on the reduction of BC emissions							Impact on the reduction of CH4 emissions
Impact on the reduction of BC emissions							Impact on the reduction of the CO2 emissions
Impact on the reduction of CH4 emissions							Impact on the reduction of the CO2 emissions

How important is criterion *Ship age* when it is compared to criterion *Ship size*?

How important is criterion *Ship age* when it is compared to criterion *Primary trade area*?

How important is criterion *Ship age* when it is compared to criterion *Sub-factors*?

How important is criterion *Ship size* when it is compared to criterion *Primary trade area*?

How important is criterion *Ship size* when it is compared to criterion *Sub-factors*?

How important is criterion *Primary trade area* when it is compared to criterion *Sub-factors*?

Please select your choice by ticking (X)

Other factors Criteria	**Expert´s preference**						**Other factors Criteria**
	Comparison of criterion using linguistic terms						
Criterion	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Criterion**
Ship age							Ship size
Ship age							Primary trade area
Ship age							Sub-factors
Ship size							Primary trade area
Ship size							Sub-factors
Primary trade area							Sub-factors

How important is criterion *Government support* when it is compared to *Externalities*?

Please select your choice by ticking (X)

Social-Political Criterion	**Expert´s preference**						**Social-Political Criteria**
	Comparison of criterion using linguistic terms						
Criteria	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Criteria**
Government support							Externalities

Appendix C. Questionnaire form to facilitate the pairwise comparison of technological alternatives with respect to each criterion, using linguistic terms

The comparison term "important" is the degree of efficiency in the pairwise comparison of technological alternatives with regards to each criterion.

Regarding *energy efficiency criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

How important is *Low sulphur fuels alternative* when it is compared to *LNG alternative*?

How important is *Low sulphur fuels alternative* when it is compared to *Methanol alternative*?

How important is *Low sulphur fuels alternative* when it is compared to *Ammonia alternative*?

How important is *HFO with scrubber alternative* when it is compared to *LNG alternative*?

How important is *HFO with scrubber alternative* when it is compared to *Methanol alternative*?

How important is *HFO with scrubber alternative* when it is compared to *Ammonia alternative*?

How important is *LNG alternative* when it is compared to *Methanol alternative*?

How important is *LNG alternative* when it is compared to *Ammonia alternative*?

How important is *Methanol alternative* when it is compared to *Ammonia alternative*?

Please select your choice by ticking (X)

Energy efficiency criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Technology reliability criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Technology reliability criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Safety criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Safety criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Maturity Criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Maturity criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Margin profit criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Margin profit criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Operational cost criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Operational cost criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Capital cost criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Capital cost criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Life cycle cost criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Life cycle cost criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Impact on the reduction of SOx emissions criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Impact on the reduction of SOx emissions criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Impact on the reduction of NOx emissions criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Impact on the reduction of NOx emissions criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Impact on the reduction of BC emissions criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Impact on the reduction of BC emissions criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Impact on the reduction of CH4 emissions criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Impact on the reduction of CH4 emissions criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Impact on the reduction of CO2 emissions criterion:*

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Impact on the reduction of CO2 emissions criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Ship age criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Ship age criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Ship size criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Ship size criterion							
	Expert´s preference **Comparison of technological alternatives using linguistic terms**						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Primary trade area criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Primary trade area criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Other sub-factors criterion*:

How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Other sub factors criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Government support criterion*:

How important is *Low sulphur fuels* alternative when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Government support criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Regarding *Externalities criterion*:

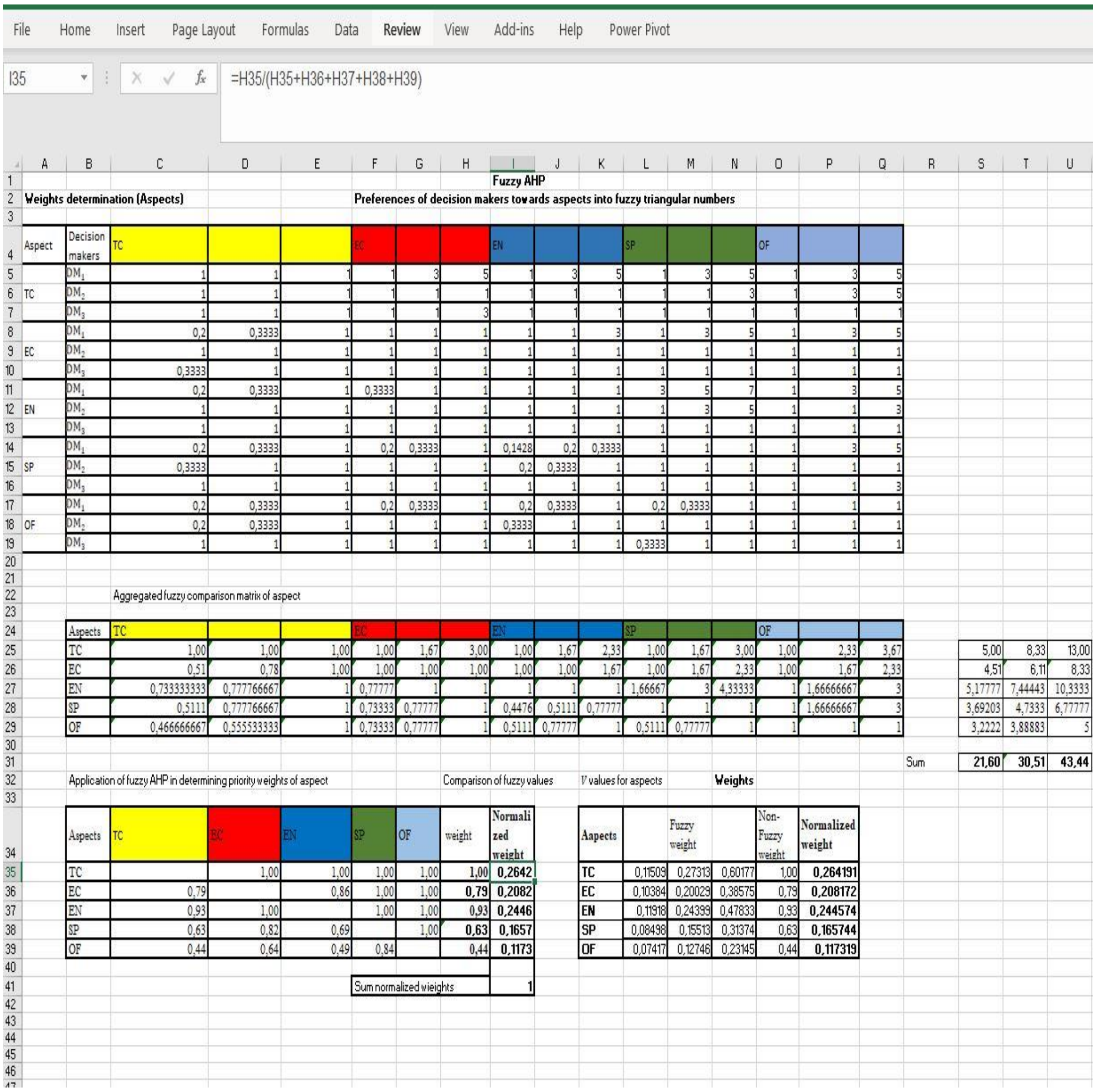
How important is *Low sulphur fuels alternative* when it is compared to *HFO with scrubber alternative*?

And so on…

Please select your choice by ticking (X)

Externalities criterion							
	Expert´s preference						
	Comparison of technological alternatives using linguistic terms						
Technological Alternatives	Equally important	Moderately important	More important	Strongly important	Very strongly important	Extremely important	**Technological Alternatives**
Low sulphur fuels							HFO with scrubber
Low sulphur fuels							LNG
Low sulphur fuels							Methanol
Low sulphur fuels							Ammonia
HFO with scrubber							LNG
HFO with scrubber							Methanol
HFO with scrubber							Ammonia
LNG							Methanol
LNG							Ammonia
Methanol							Ammonia

Appendix D. Excel template for determining weights of aspects, criteria and relative performances of alternatives using Fuzzy AHP



I35

=H35/(H35+H36+H37+H38+H39)

Fuzzy AHP

Weights determination (Aspects)

Preferences of decision makers towards aspects into fuzzy triangular numbers

Aspect	Decision makers	TC			EC			EN			SP			OF		
	DM_1	1	1	1	1	3	5	1	3	5	1	3	5	1	3	5
TC	DM_2	1	1	1	1	1	1	1	1	1	1	1	3	1	3	5
	DM_3	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1
	DM_1	0,2	0,3333	1	1	1	1	1	1	3	1	3	5	1	3	5
EC	DM_2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	DM_3	0,3333	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	DM_1	0,2	0,3333	1	0,3333	1	1	1	1	1	3	5	7	1	3	5
EN	DM_2	1	1	1	1	1	1	1	1	1	1	3	5	1	1	3
	DM_3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	DM_1	0,2	0,3333	1	0,2	0,3333	1	0,1428	0,2	0,3333	1	1	1	1	3	5
SP	DM_2	0,3333	1	1	1	1	1	0,2	0,3333	1	1	1	1	1	1	1
	DM_3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3
	DM_1	0,2	0,3333	1	0,2	0,3333	1	0,2	0,3333	1	0,2	0,3333	1	1	1	1
OF	DM_2	0,2	0,3333	1	1	1	1	0,3333	1	1	1	1	1	1	1	1
	DM_3	1	1	1	1	1	1	1	1	1	0,3333	1	1	1	1	1

Aggregated fuzzy comparison matrix of aspect

Aspects	TC			EC			EN			SP			OF		
TC	1,00	1,00	1,00	1,00	1,67	3,00	1,00	1,67	2,33	1,00	1,67	3,00	1,00	2,33	3,67
EC	0,51	0,78	1,00	1,00	1,00	1,00	1,00	1,00	1,67	1,00	1,67	2,33	1,00	1,67	2,33
EN	0,733333333	0,777766667	1	0,77777	1	1	1	1	1	1,66667	3	4,33333	1	1,66666667	3
SP	0,5111	0,777766667	1	0,73333	0,77777	1	0,4476	0,5111	0,77777	1	1	1	1	1,66666667	3
OF	0,466666667	0,555533333	1	0,73333	0,77777	1	0,5111	0,77777	1	0,5111	0,77777	1	1	1	1

	S	T	U
	5,00	8,33	13,00
	4,51	6,11	8,33
	5,17777	7,44443	10,3333
	3,69203	4,7333	6,77777
	3,2222	3,88883	5
Sum	**21,60**	**30,51**	**43,44**

Application of fuzzy AHP in determining priority weights of aspect

Comparison of fuzzy values

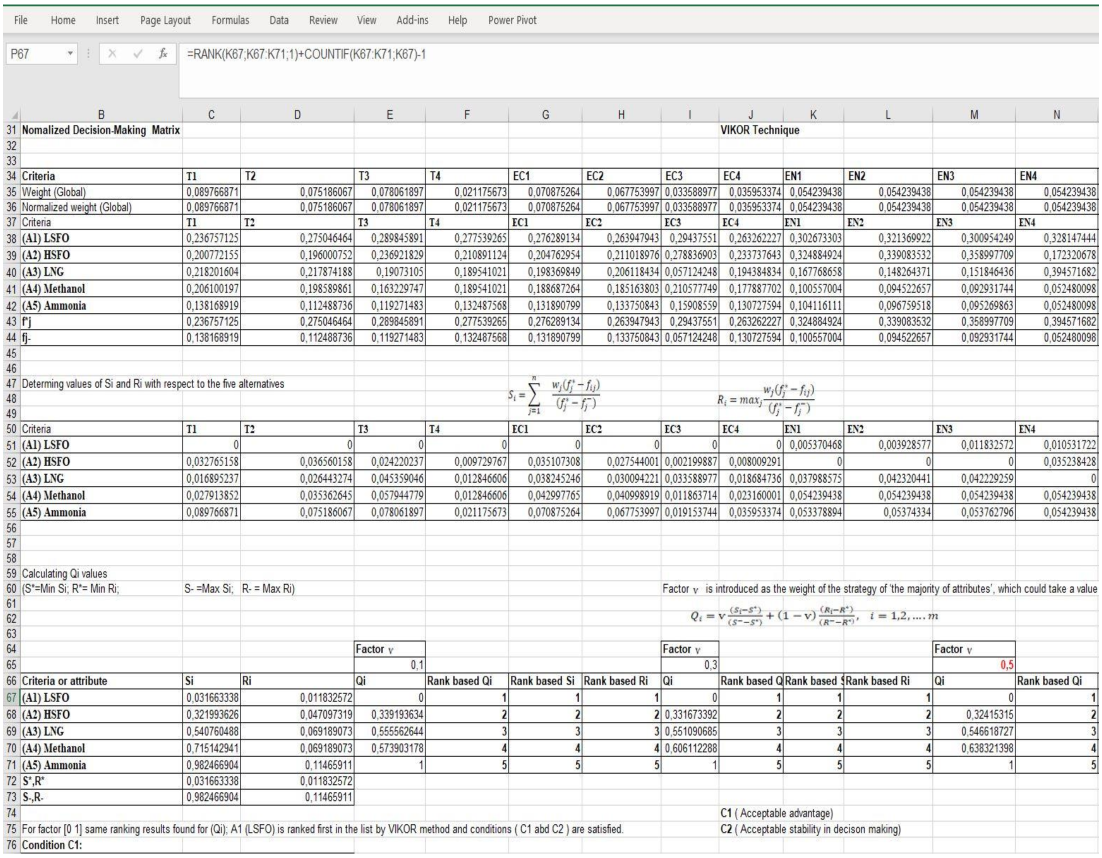
Aspects	TC	EC	EN	SP	OF	weight	**Normalized weight**
TC		1,00	1,00	1,00	1,00	**1,00**	**0,2642**
EC	0,79		0,86	1,00	1,00	**0,79**	**0,2082**
EN	0,93	1,00		1,00	1,00	**0,93**	**0,2446**
SP	0,63	0,82	0,69		1,00	**0,63**	**0,1657**
OF	0,44	0,64	0,49	0,84		**0,44**	**0,1173**
				Sum normalized wieights			**1**

V values for aspects

Weights

Aapects		Fuzzy weight		Non-Fuzzy weight	**Normalized weight**
TC	0,11509	0,27313	0,60177	1,00	**0,264191**
EC	0,10384	0,20029	0,38575	0,79	**0,208172**
EN	0,11918	0,24399	0,47833	0,93	**0,244574**
SP	0,08498	0,15513	0,31374	0,63	**0,165744**
OF	0,07417	0,12746	0,23145	0,44	**0,117319**

Appendix E. Excel template for ranking alternatives using VIKOR



```
=RANK(K67;K67:K71;1)+COUNTIF(K67:K71;K67)-1
```

Nomalized Decision-Making Matrix

VIKOR Technique

Criteria	**T1**	**T2**	**T3**	**T4**	**EC1**	**EC2**	**EC3**	**EC4**	**EN1**	**EN2**	**EN3**	**EN4**
Weight (Global)	0,089766871	0,075186067	0,078061897	0,021175673	0,070875264	0,067753997	0,033588977	0,035953374	0,054239438	0,054239438	0,054239438	0,054239438
Normalized weight (Global)	0,089766871	0,075186067	0,078061897	0,021175673	0,070875264	0,067753997	0,033588977	0,035953374	0,054239438	0,054239438	0,054239438	0,054239438
Criteria	**T1**	**T2**	**T3**	**T4**	**EC1**	**EC2**	**EC3**	**EC4**	**EN1**	**EN2**	**EN3**	**EN4**
(A1) LSFO	0,236757125	0,275046464	0,289845891	0,277539265	0,276289134	0,263947943	0,29437551	0,263262227	0,302673303	0,321369922	0,300954249	0,328147444
(A2) HSFO	0,200772155	0,196000752	0,236921829	0,210891124	0,204762954	0,211018976	0,278836903	0,233737643	0,324884924	0,339083532	0,358997709	0,172320678
(A3) LNG	0,218201604	0,217874188	0,19073105	0,189541021	0,198369849	0,206118434	0,057124248	0,194384834	0,167768658	0,148264371	0,151846436	0,394571682
(A4) Methanol	0,206100197	0,198589861	0,163229747	0,189541021	0,188687264	0,185163803	0,210577749	0,177887702	0,100557004	0,094522657	0,092931744	0,052480098
(A5) Ammonia	0,138168919	0,112488736	0,119271483	0,132487568	0,131890799	0,133750843	0,15908559	0,130727594	0,104116111	0,096759518	0,095269863	0,052480098
f*j	0,236757125	0,275046464	0,289845891	0,277539265	0,276289134	0,263947943	0,29437551	0,263262227	0,324884924	0,339083532	0,358997709	0,394571682
fj-	0,138168919	0,112488736	0,119271483	0,132487568	0,131890799	0,133750843	0,057124248	0,130727594	0,100557004	0,094522657	0,092931744	0,052480098

Determing values of Si and Ri with respect to the five alternatives

$$S_i = \sum_{j=1}^{n} \frac{w_j(f_j^* - f_{ij})}{(f_j^* - f_j^-)}$$

$$R_i = max_j \frac{w_j(f_j^* - f_{ij})}{(f_j^* - f_j^-)}$$

Criteria	**T1**	**T2**	**T3**	**T4**	**EC1**	**EC2**	**EC3**	**EC4**	**EN1**	**EN2**	**EN3**	**EN4**
(A1) LSFO	0	0	0	0	0	0	0	0	0,005370468	0,003928577	0,011832572	0,010531722
(A2) HSFO	0,032765158	0,036560158	0,024220237	0,009729767	0,035107308	0,027544001	0,002199887	0,008009291	0	0	0	0,035238428
(A3) LNG	0,016895237	0,026443274	0,045359046	0,012846606	0,038245246	0,030094221	0,033588977	0,018684736	0,037988575	0,042320441	0,042229259	0
(A4) Methanol	0,027913852	0,035362645	0,057944779	0,012846606	0,042997765	0,040998919	0,011863714	0,023160001	0,054239438	0,054239438	0,054239438	0,054239438
(A5) Ammonia	0,089766871	0,075186067	0,078061897	0,021175673	0,070875264	0,067753997	0,019153744	0,035953374	0,053378894	0,05374334	0,053762796	0,054239438

Calculating Qi values

(S*=Min Si; R*= Min Ri; S- =Max Si; R- = Max Ri)

Factor v is introduced as the weight of the strategy of 'the majority of attributes', which could take a value

$$Q_i = v\frac{(S_i - S^*)}{(S^- - S^*)} + (1 - v)\frac{(R_i - R^*)}{(R^- - R^*)}, \quad i = 1,2, \ldots m$$

			Factor v				Factor v				Factor v	
			0,1				0,3				0,5	
Criteria or attribute	**Si**	**Ri**	**Qi**	**Rank based Qi**	**Rank based Si**	**Rank based Ri**	**Qi**	**Rank based Q**	**Rank based S**	**Rank based Ri**	**Qi**	**Rank based Qi**
(A1) LSFO	0,031663338	0,011832572	0	**1**	**1**	**1**	0	**1**	**1**	**1**	0	**1**
(A2) HSFO	0,321993626	0,047097319	0,339193634	**2**	**2**	**2**	0,331673392	**2**	**2**	**2**	0,32415315	**2**
(A3) LNG	0,540760488	0,069189073	0,555562644	**3**	**3**	**3**	0,551090685	**3**	**3**	**3**	0,546618727	**3**
(A4) Methanol	0,715142941	0,069189073	0,573903178	**4**	**4**	**4**	0,606112288	**4**	**4**	**4**	0,638321398	**4**
(A5) Ammonia	0,982466904	0,11465911	1	**5**	**5**	**5**	1	**5**	**5**	**5**	1	**5**
S*,R*	0,031663338	0,011832572										
S-,R-	0,982466904	0,11465911										

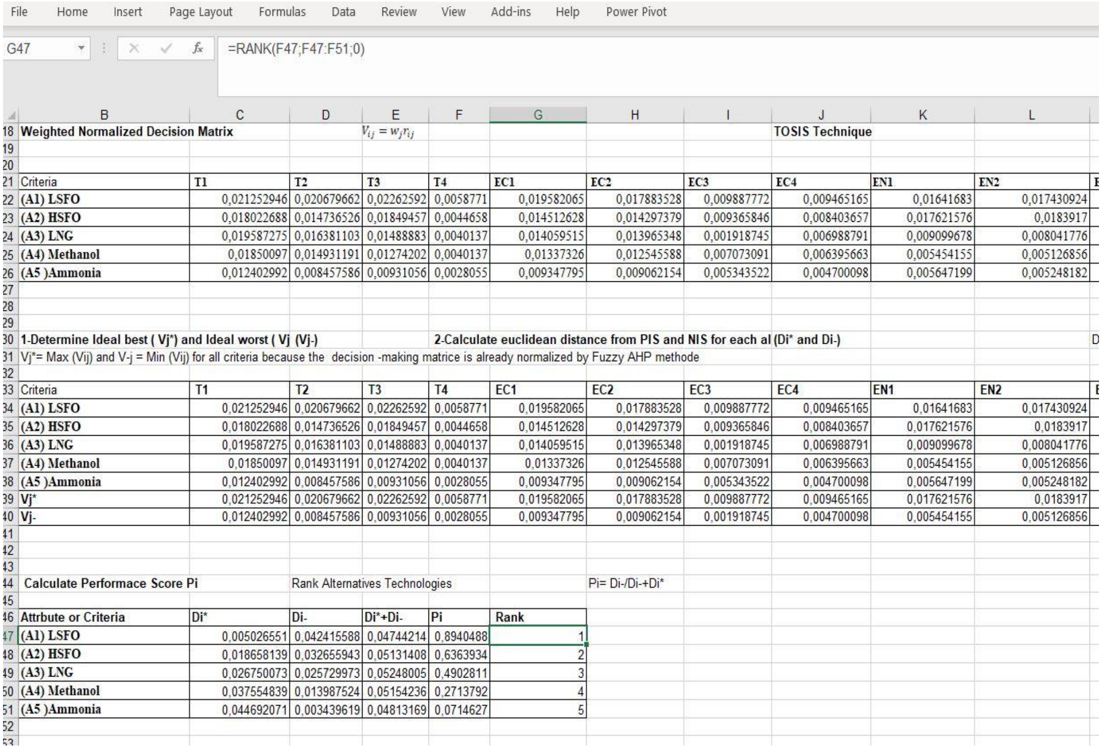
C1 (Acceptable advantage)

C2 (Acceptable stability in decison making)

For factor [0 1] same ranking results found for (Qi); A1 (LSFO) is ranked first in the list by VIKOR method and conditions (C1 abd C2) are satisfied.

Condition C1:

Appendix F. Excel template for ranking alternatives using TOPSIS



=RANK(F47;F47:F51;0)

Weighted Normalized Decision Matrix $V_{ij} = w_j r_{ij}$ **TOSIS Technique**

Criteria	T1	T2	T3	T4	EC1	EC2	EC3	EC4	EN1	EN2
(A1) LSFO	0,021252946	0,020679662	0,02262592	0,0058771	0,019582065	0,017883528	0,009887772	0,009465165	0,01641683	0,017430924
(A2) HSFO	0,018022688	0,014736526	0,01849457	0,0044658	0,014512628	0,014297379	0,009365846	0,008403657	0,017621576	0,0183917
(A3) LNG	0,019587275	0,016381103	0,01488883	0,0040137	0,014059515	0,013965348	0,001918745	0,006988791	0,009099678	0,008041776
(A4) Methanol	0,01850097	0,014931191	0,01274202	0,0040137	0,01337326	0,012545588	0,007073091	0,006395663	0,005454155	0,005126856
(A5)Ammonia	0,012402992	0,008457586	0,00931056	0,0028055	0,009347795	0,009062154	0,005343522	0,004700098	0,005647199	0,005248182

1-Determine Ideal best (Vj*) and Ideal worst (Vj (Vj-) **2-Calculate euclidean distance from PIS and NIS for each al (Di* and Di-)**

Vj*= Max (Vij) and V-j = Min (Vij) for all criteria because the decision -making matrice is already normalized by Fuzzy AHP methode

Criteria	T1	T2	T3	T4	EC1	EC2	EC3	EC4	EN1	EN2
(A1) LSFO	0,021252946	0,020679662	0,02262592	0,0058771	0,019582065	0,017883528	0,009887772	0,009465165	0,01641683	0,017430924
(A2) HSFO	0,018022688	0,014736526	0,01849457	0,0044658	0,014512628	0,014297379	0,009365846	0,008403657	0,017621576	0,0183917
(A3) LNG	0,019587275	0,016381103	0,01488883	0,0040137	0,014059515	0,013965348	0,001918745	0,006988791	0,009099678	0,008041776
(A4) Methanol	0,01850097	0,014931191	0,01274202	0,0040137	0,01337326	0,012545588	0,007073091	0,006395663	0,005454155	0,005126856
(A5)Ammonia	0,012402992	0,008457586	0,00931056	0,0028055	0,009347795	0,009062154	0,005343522	0,004700098	0,005647199	0,005248182
Vj*	0,021252946	0,020679662	0,02262592	0,0058771	0,019582065	0,017883528	0,009887772	0,009465165	0,017621576	0,0183917
Vj-	0,012402992	0,008457586	0,00931056	0,0028055	0,009347795	0,009062154	0,001918745	0,004700098	0,005454155	0,005126856

Calculate Performace Score Pi Rank Alternatives Technologies Pi= Di-/Di-+Di*

Attrbute or Criteria	Di*	Di-	Di*+Di-	Pi	Rank
(A1) LSFO	0,005026551	0,042415588	0,04744214	0,8940488	1
(A2) HSFO	0,018658139	0,032655943	0,05131408	0,6363934	2
(A3) LNG	0,026750073	0,025729973	0,05248005	0,4902811	3
(A4) Methanol	0,037554839	0,013987524	0,05154236	0,2713792	4
(A5)Ammonia	0,044692071	0,003439619	0,04813169	0,0714627	5

Appendix I. Fuzzy Analytical Hierarchy Process (Fuzzy AHP)

According to Liu et al., (2020), the principle of Fuzzy AHP method is described as follows:

The representation for the pairwise comparison is the primary step in a fuzzy AHP method to establish the pairwise comparison matrix with respect to experts' opinions, using the linguistic terms (e.g., Equal importance (EQI); Moderately importance (MI); More importance (MI); Strongly importance (SI); and Very strong importance (VSI); and Extremely strong importance (ESI)), to assign relative importance to one criterion/alternative over another criterion/alternative where a fuzzy set represents the linguistic terms; hence, a value between 0 and 1 is assigned by the membership function to each element. The correspondences between the fuzzy set and the linguistic terms must conform to fuzzy scale, which links the verbal and numerical expressions; for instance, fuzzy scales of 9 and 5 relative importance levels are widely used as depicted in Fig.1; thus, the same judgment produces the same measurable values.

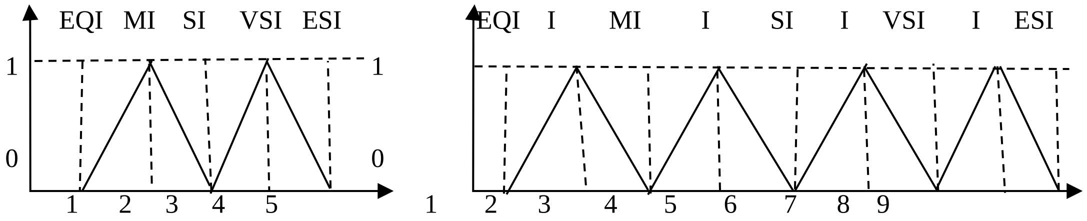


Fig. 1. Fuzzy scale of 5-level and 9-level.

Mathematically, a fuzzy number is a convex normalized fuzzy set of the real line where its associated membership function is piecewise continuous; and a crisp number can be fuzzified. Various simple and representative fuzzy types have been proposed, for instance, trapezoidal fuzzy number and (TraFN) Triangular fuzzy number (TFN), to facilitate data processing such as arithmetic operations.

TFN is the most popular means of judgement representation and is easy to compute. It can be represented as a triple $\tilde{A} = (l, m, u)$, where l and u are respectively the smallest and the largest values with the smallest membership, but m is the value with the largest membership, as illustrated by Figure 4 (a). The TFN´s membership function is determined as follows (Eq.1).

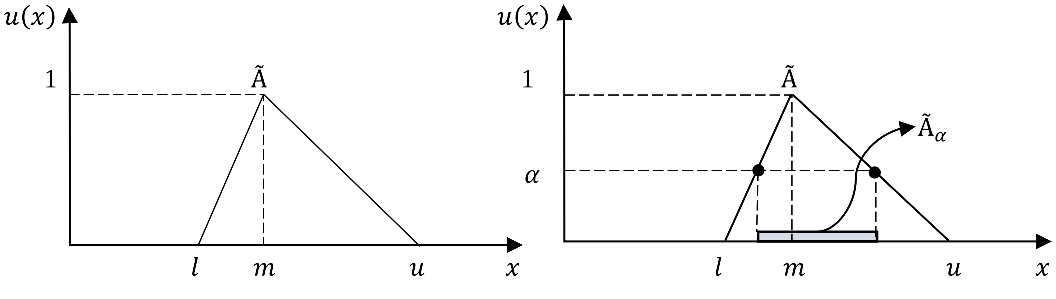
$$u(x) = \begin{cases} \frac{x-l}{m-l} & , \ l \leq x \leq m \\ \frac{(u-x)}{(u-m)} & , \ m \leq x \leq u \end{cases} \quad (1)$$

The a-cut set of a fuzzy set Ã described as $\tilde{A}_{\alpha}$, is a crisp value set including all the elements with membership degrees greater than or equal to the specified value of α, as illustrated in Figure 4 (b) and Eq. (3).

$$\tilde{A}_{\alpha} = \{x, u(x) \geq \alpha \} \quad (2)$$

The a-cut set of a TFN can be depicted as an interval, as shown in Figure 4 (b). It helps de-fuzzily a TFN.

$$\tilde{A}_{\alpha} = [l + (m - l)\alpha, u - (u - m)\alpha] \quad (3)$$



(a) (b)

Figure 2. (a) A TFN, Ã; (b) α -cut of a TFN, $\tilde{A}_{\alpha}$

Appendix G. The pros and cons of the five alternatives selected for the case study

Alternative technologies	Pros	Cos
HSFO	-Outperforms other fuels in terms of total SO_2 (associated SOx) emissions during all life cycle processes (Bilgili, 2021). -Scrubbers can reduce SO_X emissions by more than 95%, and by about 50% to 60% of PM emissions including BC emissions (Zisi et al., 2021).	-The least suitable option for both global warming potential (GWP) and non-GWP gases ((Bilgili, 2021) -The CO_2 footprint associated with the use of a scrubber, as a compliant fuel option, increase from 1.5% to 3% (well-to-wake CO_2 emissions) (Faber et al., 2020). -Dump acidic washing water and toxic mixture from the scrubber into the ocean that will damage the marine environment (Teuchies et al., 2020). -The costs of installing scrubbers' on board ships are costly and they are difficult to retrofit on small ships (Peng et al., 2021). -The installation costs of the different types of scrubbers are estimated at around 2-3 million euros (Bergqvist et al., 2015). -Retrofitting an existing ship typically costs 40% more than the installation of a scrubber on a new ship (Zhu et al., 2020).

LSFO	-LCA-Total environmental effects are higher than other fuels (Bilgili, 2021). -Blended VLSFOs can achieve low fuel prices and can be produced in sufficient quantities in the refinery compared to other compliant fuels ISO 8217 DM quality specifications; for instance, marine diesel (MDO) and gas oil (MGO) (Einemo, 2020).	-VLSFOs (blends) has the highest black carbon aerosol (BCA) (Bilgili, 2021). -An increase in the CO2 footprint, well to wake, of 1% and 25% in refinery is projected during the desulfurization process to produce VLSFOs; principally due to the process itself and throughout refining the fuels depend to the level of desulfurization and the quality of the fuel produced (Faber et al., 2020). -The price of VLSFO (0,5%m/m Sulphur content) is 30% higher than that of HFO (Peng et al., 2021). -Technical changes, on board ships, were mainly required for adaptability of engines related to the quality and the propriety of VLSFOs available in the market (CANCA & Kökkülünk, 2020).

LNG	-LNG fuelled engines have lower fuel costs per kWh (Output) (Balcombe et al., 2021). -LNG as a marine fuel is considered one of the most promising alternative marine fuels in terms of economy and environmental benefits (Deng, 2021). -LNG as a fuel reduces SO_X and particulate matter (soot) emissions, CO2 emissions and NOx emissions by 95-100%, up to 25% and up to 90%, respectively, compared to traditional marine fuels such as HFO (Æsøy & Stenersen, D. 2013; Choi et al., 2020) -Reduce GHGs up to 21% (WtW) (Sphera, 2019). -Reduce GHGs up to 28 % (TtW) (Sphera, 2019). -May offer ~30% reduced CO2 emissions (Balcombe et al., 2021). -Enable IMO Tier III compliance (Sphera, 2019).	-Issue with methane slip (Sphera, 2019). -Methane emissions must be reduced to 0.8-1.6% to ensure a climate advantage over HFO. -More than 10% of boil-off gas is released as methane emissions for a storage period of only 0 to 2 days (Balcombe et al., 2021). -GHG emissions resulting from CH_4 emissions account for around 3 % of the total WtW GHG emissions of oil-based fuels (Sphera, 2019). -Capital costs vary 5–40% higher than diesel engines (Balcombe et al., 2021). -With methane emissions reduced to 0.5% of throughput, energy efficiency must increase 35% to meet a 50% decarbonisation target (Balcombe et al., 2021). -Issues with boil-off gas (BOG/LNG) in marine transportation and storage facilities as well as along LNG supply chains, resulting in more CH_4 emissions into the atmosphere due to some existing operational inefficiencies (Perez et al., 2021; Kochunni & amp; Chowdhury, 2021).

		-The retrofitting of ship with LNG fuel is estimated to cost of up to 20% to 30% of the price of the ship because it requires an upgrade of the installation on board; such as, installing a LNG tank, a fuel gas supply system, and a gas value unit (Li et al.,2020).
Methanol	-Lower CO_2 and does not emit SO_X emissions and extremely decreases PM emission formation (Zincir & Deniz,2021). -Lower NO_X emissions by 30% (Svanberg et al., 2018). -PM emissions are significantly lower than for fuel oils and similar to what is found for LNG engines (Fridell et al., 2020). -Methanol from natural gas performs well for air quality but poorly for both short and long-term climate impacts (Balcombe et al., 2021). -Methanol is a unique fuel that can provide high	-The emission factor for nitrogen oxides does not reach the tier III limit (Fridell et al., 2021). -Produce higher life cycle GHG emission than conventional fuels. -Must be produced from renewable feedstock/ biomass to offers great potential to reduce the life cycle GHG emission compared to conventional fuel oils (Liu et al.,2019). -Methanol is worst for cost. It is 10–140% higher than HFO (Balcombe et al., 2021).

	engine efficiency and low emissions than diesel fuel (Zincir & Deniz, 2021) -Required space and a very toxic chemical (ABS, 2021).	
Ammonia	-Low GHG emissions (Al-Aboosi, 2021). -Free carbon fuel, having zero SO_X and CO_2 emissions (Cheliotis et al., 2021).	-Environmental benefits are improved when it is produced from renewable energy and feedstocks. (Al-Aboosi, 2021). -Ammonia's high nitrogen content, its combustion in high temperatures leads to increased NO_X emissions (Cheliotis et al., 2021). -Larger space requirement onboard ships than LNG and methanol cryogenic storage, which is required for liquefied hydrogen. -The additional propulsion system cost for an ammonia-fuelled vessel with an internal combustion engine has been estimated to approximately 2–60% compared to a conventional HFO-fuelled vessel. -Ammonia is a toxic substance. (Hansson et al., 2020; ABS, 2020).