Chapter 5
Investigation and Examination of LNG, Methanol, and Ammonia Usage on Marine Vessels

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Abstract This study aims to evaluate the use of LNG, methanol, and ammonia on ships as an alternative marine fuel. In this sense, firstly, the SWOT analysis is conducted, so the strengths and weak sides of the alternative fuels are determined. In the second step of the study, various criteria such as safety, cost, exhaust emission, global warming potential, sustainability, storage, and technical competence are specified, and the alternative fuels are analyzed with the TOPSIS method based on the identified criteria. As a result of the obtained judgments from the marine experts, the safety of fuel, its global warming potential, and its storage feature is determined as the most influential comparison weights. In addition, ammonia is determined as the best fuel option based on the 2.92 similarity value while values of LNG and methanol are calculated 2.21 and 2.18, respectively. Then, a sensitivity analysis where the various cases were created by improving the weights of criteria by 25% and applying the same weight value for each criterion is conducted to reveal the criticality of the criterion weighting. According to this analysis, it is observed that the analysis is highly sensitive to the global warming potential criteria. In line with this information, beneficial and significant key findings to policy-makers, stakeholders, and maritime companies are presented from the perspectives of short-term and long-term emission reduction strategies.

Keywords Maritime · Alternative marine fuel · SWOT · TOPSIS · Sensitivity analysis

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Abbreviations

AHP	Analytic hierarchy process
LCA	Life cycle assessment
BOG	Boil-off gas
LNG	Liquefied natural gas
CI	Compression ignition
LD	Light duty
DICI	Direct injection compression ignition
DI	Direct injection
ECA	Emission control area
MCDM	Multi-criteria decision-making
GHG	Greenhouse gas
MDO	Marine diesel oil
HFO	Heavy fuel oil
SWOT	Strengths, weaknesses, opportunities, and threats
IMO	International maritime organization
TOPSIS	Technique for order of preference by similarity to ideal solution

5.1 Introduction

Maritime transportation is a significant part of the global cargo supply chain and provides 80% of world trade (UNCTAD 2017; Elidolu et al. 2022). Eight billion tons of international trade goods have been carried by shipping every year (Du et al. 2011). Ensuring high-volume transportation, high-powered ship diesel engines with various integrated complex systems were used in the ship engine rooms (Ceylan et al. 2022a, b). As a result of the high fuel consumption required by these high-power diesel engines during ship transportation, exhaust gas emissions are generated. The International Maritime Organization (IMO) which steers the shipping sector has been stated in the 3rd greenhouse gas study that approximately 300 million tons of fuel which are mostly heavy fuel oil (HFO) were consumed annually (IMO 2014). As a result of the combustion of the HFO, serious amounts of pollutants such as CO_2, SO_x, and NO_x have been emitted into the atmosphere (Ceylan et al. 2022b; Karatuğ and Arslanoğlu 2022). It has been presented by the IMO that the portion of the maritime sector in global anthropogenic emissions is 2.89% in 2018 (IMO 2020).

Due to the harmful effects of these types of emission gases, IMO introduced some emission-related rules (IMO 1997). Additionally, the IMO defined the decarbonization strategy of the maritime sector (IMO 2018) to reduce pollution caused by ships. Accordingly, it is aimed to reduce total annual greenhouse gas (GHG) emissions by at least 50% by 2050, compared to 2008. To decrease the amounts of SO_x, after 1 January 2020, the sulfur content limit of the fuel is reduced from 3.50% m/m to 0.50% m/m for ships that navigate on open seas as shown in Fig. 5.1, while it is

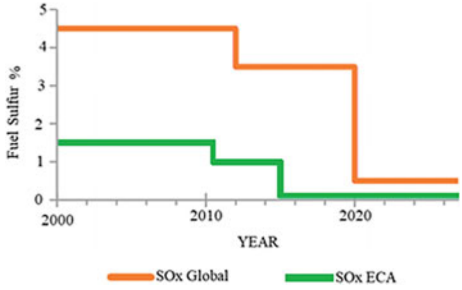


Fig. 5.1 IMO sulfur limits (IMO 2020)

determined as 0.01% m/m for ships where navigate in emission control areas (ECA). Also, some limits for the NO_x were defined accordingly. These strict rules force shipping companies and operators to research emission reduction approaches and implement these methods in their ships. In this sense, different research areas such as the use of alternative energy sources (Karatuğ and Durmuşoğlu 2020), exhaust gas treatment applications (Deng et al. 2021), and investigation of green alternative fuels (Deniz and Zincir 2016) stand out in the maritime sector.

In the 4th IMO GHG study, it was presented that HFO is still the most widely used marine fuel with 79%. On the other hand, it is understood that the use of marine diesel oil (MDO) and liquefied natural gas (LNG) as main fuels in the world fleet has increased with the last sulfur limitation that came into effect in 2020. It was also stated in the study that methanol is the 4th most common marine fuel. In addition to these fuels, ammonia is one of the promising fuels for the maritime industry due to its carbon-free structure and its compliance with the decarbonization target determined by IMO (Kim et al. 2020a).

Each of the specified alternative marine fuels has both different advantages and disadvantages. In this study, LNG, methanol, and ammonia, which are recently been intensively researched as alternative marine fuels, were examined with strengths, weaknesses, opportunities, and threats (SWOT) analysis. Then, some criteria to be important for the preference of the alternative marine fuel have been determined and analyzed by the technique for order of preference by similarity to ideal solution (TOPSIS) method which is one of the most common multi-criteria decision-making (MCDM) methods. Lastly, a sensitivity analysis was performed to observe the importance level of each criterion for the similarity values of each alternative marine fuel. As a result of the analysis, ammonia is found as the best fuel alternative, while the most critical comparison criterion is stated as global warming potential. The LNG has currently practical implementation, so its technical competency is superior to methanol. However, the closeness of the similarity values of the LNG and methanol could be interpreted as methanol can be an alternative to LNG when its technical competence is sufficiently developed.

For researchers interested in this field and maritime companies, the proposed methodology enables both firstly, to evaluate the advantages and disadvantageous sides of the alternatives within the SWOT analysis and secondly, to determine the best option according to the general intention of the expert consortium. In addition, different from the relevant literature, the inclusion of SWOT analysis in the proposed approach has enhanced the influence level of the selection of fuel alternatives via methodology by handling each fuel option from different points of view.

5.1.1 Literature Review

There are some studies about alternative fuels in the literature. They have been either examined individually or analyzed comparatively. Pucilowski et al. (2017) investigated the methanol-fueled heavy-duty direct injection compression ignition (DICI) engine combustion characteristics by using the start of injection effect. Zincir et al. (2019a) use an experimental approach to investigate how intake temperature affects the low load limits of partially premixed combustion of the same alternative fuel (methanol). Iannaccone et al. (Iannaccone et al. 2020) evaluated LNG under some environmental and safety factors and proposed that compared to the diesel-fueled system, the LNG system was 41% and 61% more effective in terms of environment and safety, respectively. Ammar (2019) evaluated the application of a methanol dual-fuel engine for a container ship from an environmental and economic perspective. He presented that the dual-fuel system would provide savings in 12 years, while reductions occurred in emission releasing. Hansson et al. (2020) evaluated ammonia as a future marine fuel. They stated that although it is a potential fuel due to its low environmental damage, significant technical applications should be structured and developed.

Perčić et al. (2021) carried out the economic analysis of different alternative marine fuels using the life cycle assessment (LCA) method. They stated that although methanol is the most cost-effective fuel, the necessary system bunkering infrastructure should be developed. Al-Breiki and Bicer (2020) realized the energy and exergy analysis of the three fuels studied in the study and calculated boil-off gas (BOG) ratios of them. They found that the most loss of fuel occurs in LNG systems. McKinlay et al. (2021) calculated that the maximum power demand per voyage is 9270 MWh, based on raw shipping data. Accordingly, ammonia, hydrogen, and methanol systems that can provide this power have been designed, and these systems are examined under sub-headings: storage infrastructure, desired design range, and both. Xing et al. (2021) discussed future alternative marine fuel options and presented that renewable methanol is the most promising fuel option globally, and ammonia is useful in domestic and short-sea shipping.

Wan et al. (2015) carried out a hybrid methodology based on SWOT analysis and the analytic hierarchy process (AHP) to evaluate the development of LNG-fueled ships in the inland waters of China. Some studies, on the other hand, examined duel fuel or more fuel blends instead of focusing on a single fuel. Di Blasio et al. (2017) used a dual fuel (methane-diesel) for the investigation of the performance, emissions, and particle size distributions of light duty (LD) diesel engine. Fraioli et al. (2017) carried out another dual-fuel study. They investigate the combustion of methane and diesel fuel mixture on LD diesel engines by utilizing multidimensional simulations. Balasubramanian et al. (2021) used waste cooking oil biofuel and diesel blends to investigate the emission, performance, and combustion of a single-cylinder compression ignition (CI) engine. Kumar et al. (2021) carried out diesel and methanol fuel mixture combustion, performance, and emission analysis in CI Engine. Shamun et al. (2018) carried out performance and emissions analysis of diesel, biodiesel, and ethanol blends in a single-cylinder LD CI engine. With a similar approach, Belgiorno et al. (2018) investigate the performance of diesel, gasoline, and ethanol blends in an LD CI engine.

The rest of the paper is organized as follows. The brief information for specified marine fuels, SWOT analysis, TOPSIS method, and methodological approach is presented in Sect. 5.2. The case study is conducted in Sect. 5.3. In the final, the key findings of the paper are presented in Sect. 5.4.

5.2 Materials and Methodology

5.2.1 Alternative Marine Fuels

The utilization of alternative marine fuel sources instead of HFO is a significant method to reduce emissions. There is a strong trend toward the use of alternative fuels with the intent of reducing the environmental impacts of shipping. Today, many researchers are conducting various scientific research on this current issue (Hansson et al. 2019; Paulauskiene et al. 2019; Perčić et al. 2020; Lunde Hermansson et al. 2021; Chu et al. 2019). Within the scope of this study, brief information about the use of LNG, ammonia, and methanol as marine fuels has been given in this section.

5.2.1.1 Liquefied Natural Gas

LNG is an environmentally friendly fuel type in the gas state that has been started to use as the main energy source of many vessels. Additionally, it can be used with other fuels in dual-fuel engines (Bilgili 2021). With the recent international restrictions, developing technology, and maritime field economics, LNG is becoming attractive marine fuel. LNG provides a 25% CO_2 reduction compared to HFO (Iannaccone et al. 2020). After the combustion process, a low rate of NO_x and PM has been produced by LNG usage compared to the HFO and also, and it is not released SO_x (Kim et al. 2020b). Moreover, LNG has a fair price when compared to other alternative marine fuels. However, LNG also has some risks, for instance, it must be stored in very well insulated tanks and needs more storage space. Therefore, this may cause additional costs. The other disadvantage of LNG is that this fuel alone cannot comply with the international requirements of 50% CO_2 reduction (DNV GL 2019).

5.2.1.2 Methanol

The other alternative marine fuel is methanol. With the IMO 2020 regulations, it can be used to reduce emissions. Methanol, CH_3OH, is a simple oxygenated hydrocarbon that ranks in the top five of the most traded chemicals in the world (Verhelst et al. 2019; Zincir et al. 2019b). It is a liquid and a sulfur-free corrosive fuel. It easily burns with CO_2 and H_2O, emitting no SO_x and low NO_x and PM. Methanol can be obtained from natural gas or coal. The simplest alcohol, methanol, has a low flash point, and it is a very risky marine fuel due to toxicity. It is a highly flammable gas because its calorific value has been calculated as 20,000 MJ/t (Bilgili 2021; Gilbert et al. 2018). Methanol is used in some successful marine trials and commercial projects as fuel (Liu et al. 2019). It has a low flash point at 11 °C, which does not comply with the safety of life at sea convention of IMO. However, according to the studies, a double-wall design of methanol components can solve this problem (Ammar 2019).

5.2.1.3 Ammonia

Ammonia (NH_3) is an increasingly studied, sustainable fuel for global use in future. It is a carbon-free alternative fuel that is utilized in many sectors such as healthcare, plastics, textiles, cosmetics, nutrition, and electronics (Hansson et al. 2020). Additionally, ammonia can be used in diesel engines, gas turbines, and fuel cells (Kim et al. 2020b).

Ammonia includes 1 nitrogen and 3 hydrogen atoms. In addition to its carbon-free structure, it is also a sulfur-free molecule. Therefore, combustion products of ammonia do not contain CO, CO_2, or SO_x emissions. After the ignition, only water and nitrogen products are formed. Ammonia is liquefied by 10 bar pressure at room temperature, or by −33 °C atmospheric pressure. Ammonia, which produces around 175 million tons per year worldwide, compared to liquid hydrogen, transportation, and pipeline transfer technology, is advanced for the current industry (MacFarlane et al. 2020). It is considered a strong alternative to hydrogen fuel (Bilgili 2021). However, ammonia is hardly ignited fuel, and compared to the other alternative fuels, it is toxic for both humans and the environment. Additionally, considering the fuel system and its components, ammonia is a corrosive substance (Zincir 2020).

5.2.2 SWOT Analysis

SWOT analysis can be performed with the analysis of the current situation as a whole and its internal and external environment (Olabi et al. 2022). This analysis aims to reveal the current situation, determine priorities, and identify strategic issues for progress and development. Analyzing the internal environment is a method that allows revealing the opportunities and threats by analyzing the external environment while identifying the strengths and weaknesses (Stavroulakis and Papadimitriou 2017). Strengths are the capabilities and assets that enable the situation to gain an advantage over its competitors and are both practical and efficient. On the other hand, weaknesses refer to situations where it is more inadequate, inefficient, ineffective, and powerless than its competitors. Variables consist of technological, social, cultural, economic, and global environmental elements, and the positive results of these elements for current situations are opportunities. Threats include situations that occur due to the change in external environmental factors, which may prevent the business from continuing its existence or cause it to lose its competitive advantage (Hossain et al. 2017; Al-Haidous et al. 2022; Efe et al. 2022). The SWOT analysis identifies critical internal and external factors, allowing weaknesses to be reduced and strategic planning for threats to be created effectively while taking strengths and opportunities into account.

5.2.3 TOPSIS Method

The TOPSIS method, based on the idea of approaching the ideal solution, allows the identification or selection of the optimal choice in any situation requiring decision-making by computing the positive and negative ideal solution distances (Wang et al. 2022). The method can handle very constrained decision criteria and effectively solve the decision problem. In addition, the TOPSIS method enables the creation of a standardized matrix, often derived from expert experience, in determining weights for criteria. TOPSIS facilitates analysis by assigning functions to evaluations and digitizing them, allowing for joint decision-making in problems involving many criteria and alternatives (Yang et al. 2022). The most prominent feature is that the importance weights of the criteria are different from each other. It is a convenient method for solving problems effectively and thus provides the ability to deal with uncertainty in decision-making (Bin Din et al. 2022; Zhang et al. 2022; Chrysafis et al. 2022). The algorithmic phases of the TOPSIS methods were presented as follows:

Step 1: The decision matrix is an $M \times N$ dimensional matrix created by the decision-maker after the decision options, and evaluation criteria are determined.

$$a(ij)_{M \times N} \tag{5.1}$$

where N and M are the numbers of decision options and evaluation criteria.

Step 2: A standard decision matrix (normalized matrix) is created. If the value of any element of the decision matrix is 0, the value of the relevant component in the standard decision matrix will also be 0. The normalized decision matrix can be defined as follows:

$$a_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{M} (x\text{ij})2}} \quad (5.2)$$

Step 3: A weighted standard decision matrix is created. Weight values for evaluation criteria are determined. A weighted standard decision matrix is formed by multiplying the elements of the matrix with their respective weight values.

$$X_{ij} = a_{ij} \times w_{ij} \quad (5.3)$$

$$w_{ij} = \frac{w_j}{\sum_{j=1}^{N} w_j} \quad (5.4)$$

$$\sum_{j=1}^{N} w_j = 1 \quad (5.5)$$

Step 4: Positive ideal and negative ideal solution values are obtained.

$$S^* = max_{i=1}^{M} X_{ij} \quad (5.6)$$

$$S^- = min_{i=1}^{M} X_{ij} \quad (5.7)$$

Step 5: The distance values to the positive ideal and negative ideal solution values are obtained.

$$d^* = \sqrt{\sum_{j=1}^{N} \left(X_{ij} - S^*\right)2} \quad (5.8)$$

$$d^- = \sqrt{\sum_{j=1}^{N} \left(X_{ij} - S^-\right)2} \quad (5.9)$$

Step 6: The distances of each alternative from the positive and negative perfect solutions are calculated.

$$S_{SV} = \frac{d^-}{d^* + d^-}, i = 1, 2, 3, \ldots, n \quad (5.10)$$

where $0 \leq S_{SV} \leq 1$ is the share of the distance to the ideal solution in the total distance. Accordingly, S_{SV} decision options close to 1 are preferred primarily.

5.2.4 Methodical Approach

While alternative fuels are a major topic in the marine industry, there are diverse perspectives on which fuel would be the most beneficial. In this study, frequently used LNG, methanol, and ammonia fuels in the literature were evaluated, and the best alternative was determined. For this purpose, the methodological approach of the study was designed. In this framework, the methodological approach of the study consists of two steps. The first step includes the SWOT analysis of specified alternative marine fuel types. The second stage of the study continues with the help of the data obtained by revealing the strengths-weaknesses and threats-opportunities of the fuels. This step of the study includes the evaluation of alternative marine fuels with the MCDM method. To conduct analysis, some criteria were determined based on SWOT analysis conducted and research on relevant literature (Hansson et al. 2020, 2019; Balcombe et al. 2019; Inal et al. 2022; Inal and Deniz 2020; Andersson et al. 2020). The TOPSIS approach was used to analyze fuel options based on the criteria such as safety, cost, exhaust emission, global warming potential, sustainability, storage, and technical competence. Experts were asked to score the importance of each criterion and three fuel types based on these criteria. Finally, the best fuel alternative was determined once the score was received. The methodical approach of the study was demonstrated in Fig. 5.2.

Engineers and academicians who have worked on ships using various fuel types were employed as experts in the study. Table 5.1 shows the profiles of the experts who participated in the study.

5.3 Case Study

In this paper, firstly, the specified alternative fuels were examined by SWOT analysis. Thus, the advantageous and disadvantageous aspects were determined, and the main criteria to be considered in the selection of alternative fuels were revealed. Secondly, a useful strategy to select the most suitable alternative marine fuel is presented. The LNG, methanol, and ammonia have been analyzed based on some criteria such as safety, cost, exhaust emission, global warming potential, sustainability, storage, and technical competence through the TOPSIS method.

5.3.1 SWOT Analysis of Alternative Marine Fuels

The SWOT analysis was performed using some studies from the literature, and the results were used to identify the strengths, weaknesses, opportunities, and threats of alternate marine fuels. The obtained results are presented in Appendix 5.1.

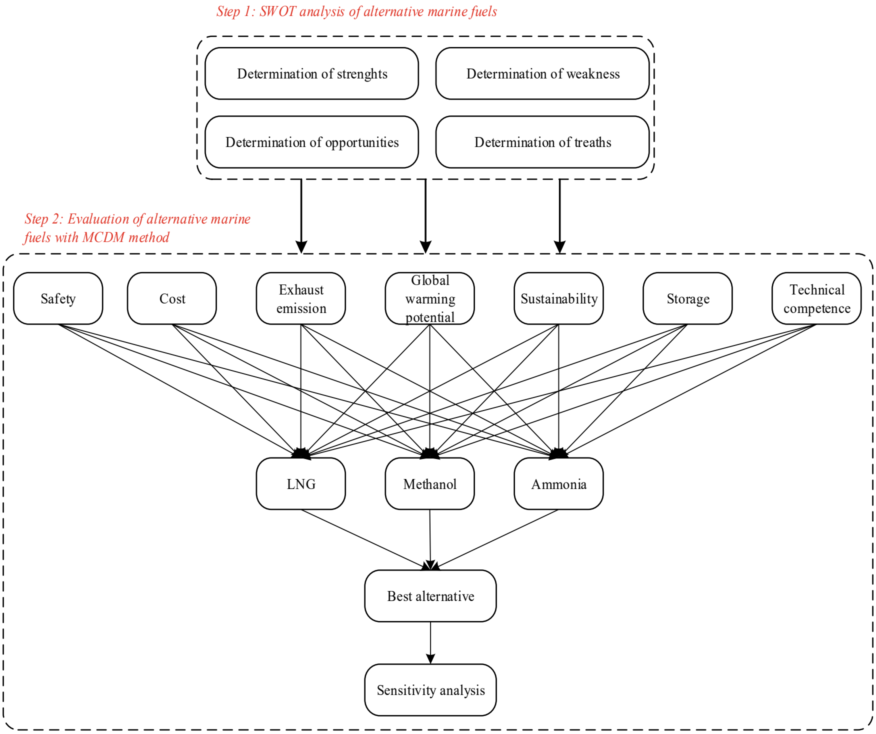


Fig. 5.2 Methodical approach of the study

Table 5.1 Expert profiles of the study

Experts	Ship experience	Current position
Expert 1	Chief Engineer	Shipping Company-Oceangoing Chief Engineer
Expert 2	Chief Engineer	Shipping Company-Oceangoing Chief Engineer
Expert 3	Chief Engineer	Shipping Company-Oceangoing Chief Engineer
Expert 4	First Engineer	National Maritime Authority-Port State Control Officer
Expert 5	First Engineer	University-Academician
Expert 6	First Engineer	Shipping Company-Oceangoing First Engineer
Expert 7	Second Engineer	University-Academician

5.3.2 TOPSIS Application

In the second part of the methodology, the specified alternative marine fuels were analyzed by TOPSIS. The alternative fuels were evaluated based on some significant criteria related to alternative selection such as safety, cost, exhaust emission, global warming potential, sustainability, storage, and technical competence.

Table 5.2 Performance scores for criteria

Criteria	Performance scores	
Importance of criteria	1-Worst	5-Best
C1- Safety	1-Worst	5-Best
C2- Cost	1-Most expensive	5- Most economic
C3- Exhaust emission	1-Worst	5-Best
C4- Global warming potential	1-Worst	5-Best
C5- Sustainability	1-Worst	5-Best
C6- Storage	1-Worst	5-Best
C7- Technical competence	1-Worst	5-Best

The analysis was realized based on the scores received by marine experts who are marine engineers or academicians in the maritime field. Four of the marine experts work on ships, and they have operational experience with different types of marine fuel. Two of the marine experts have sea service experience and currently, work at the university. One of the marine experts is the first engineer and works as the port state control officer. In the first stage, marine experts were asked to judge the criteria and criterion weights based on the information presented in Table 5.2.

The decision matrix was formed by taking the average of the scores obtained from the experts. The constituted decision matrix is as in Table 5.3.

The aggregated decision matrix was normalized using Eq. 5.2. Then, a weighted normalized decision matrix was created by introducing weights of each criterion to normalized values. It is presented in Table 5.4.

Based on values in Table 5.5, the best S^* and worst S^- alternatives are determined and presented in Table 5.6.

The next step of the analysis is the calculation of distances between the target alternative and both the best alternative and worst alternative. These calculations were realized using Eqs. 5.8 and 5.9. After calculation of the distances, the similarity value S_{SV} to the worst alternative for each alternative was determined. While $S_{SV} = 1$

Table 5.3 Decision matrix

Criteria	Weight	Alternatives		
		LNG	Methanol	Ammonia
C1	3.86	3.71	3.14	2.71
C2	3.00	3.29	3.29	2.14
C3	3.29	3.14	3.14	4.00
C4	3.86	2.00	2.57	4.29
C5	3.14	3.14	3.14	2.86
C6	3.43	2.43	3.86	3.14
C7	3.14	3.71	2.71	2.00

Table 5.4 Weighted normalized decision matrix

Criteria	Alternatives		
	LNG	Methanol	Ammonia
C1	2.57	2.18	1.88
C2	1.93	1.93	1.26
C3	1.73	1.73	2.20
C4	1.43	1.84	3.07
C5	1.87	1.87	1.70
C6	1.50	2.39	1.95
C7	2.33	1.70	1.25

Table 5.5 Best and worst alternatives

Criteria	S^*	S^-
C1	2.57	1.88
C2	1.93	1.26
C3	2.20	1.73
C4	3.07	1.43
C5	1.87	1.70
C6	2.39	1.50
C7	2.33	1.25

Table 5.6 Determination of best alternative

Alternatives	d^*	d^-	S_{SV}
LNG	1.92	1.45	2.21
Methanol	1.51	1.31	2.18
Ammonia	1.52	1.76	2.92

means that the alternative is the best solution, $S_{SV} = 0$ represents that the alternative is the worst solution. The best and worst distances of each alternative and their similarity values are presented in Table 5.6.

5.3.2.1 Sensitivity Analysis

Sensitivity analysis is an important application for MCDM studies. It provides an important projection of how effective the identified criteria are on the result obtained. In particular, the scores obtained in an MCDM application developed based on expert opinion are subjective, no matter how much they are obtained from experts that work

Table 5.7 Formed cases for sensitivity analysis

Case	Description	Weight of criterion						
		C1	C2	C3	C4	C5	C6	C7
Base case	Base condition weighting	3.86	3.00	3.28	3.85	3.14	3.42	3.14
Equal weights	Equal weighting	**3.39**	**3.39**	**3.39**	**3.39**	**3.39**	**3.39**	**3.39**
Case 1	C1 + 25% weighting	**4.83**	3.00	3.28	3.85	3.14	3.42	3.14
Case 2	C2 + 25% weighting	3.86	**3.75**	3.28	3.85	3.14	3.42	3.14
Case 3	C3 + 25% weighting	3.86	3.00	**4.11**	3.85	3.14	3.42	3.14
Case 4	C4 + 25% weighting	3.86	3.00	3.28	**4.83**	3.14	3.42	3.14
Case 5	C5 + 25% weighting	3.86	3.00	3.28	3.85	**3.93**	3.42	3.14
Case 6	C6 + 25% weighting	3.86	3.00	3.28	3.85	3.14	**4.29**	3.14
Case 7	C7 + 25% weighting	3.86	3.00	3.28	3.85	3.14	3.42	**3.93**

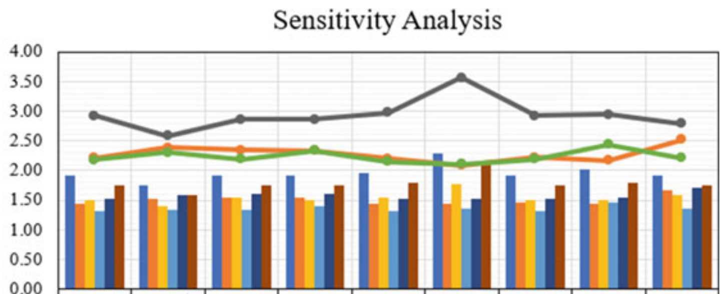
in the relevant field. Therefore, the results could vary in the evaluation conducted by a different consortium of experts (Inal et al. 2022). At this point, the sensitivity analysis reveals the effect of the changes in the weights of the criteria on the result obtained and enables the determination of critical criteria. In the sensitivity analysis, the various cases were created by improving the weights of criteria by 25% and applying the same weight value for each criterion. The formed cases for sensitivity analysis and weights of criterion for each case are illustrated in Table 5.7.

The same calculations with the base case have been made for each formed case. The effects of changes on the distance to best and worst alternatives and similarity value were observed. The changes that occurred as a result of the calculations made within the scope of the sensitivity analysis are illustrated and presented in Fig. 5.3.

The rank of the preference of the specified alternative marine fuels was mostly observed as Ammonia > LNG > Methanol. However, it should be underlined that LNG and methanol have generally close similarity values in cases created. It is observed that the similarity value of the methanol is raised with increasing the weight of the storage criteria since the storage of methanol could be achieved with a small arrangement for the existing ships. For ammonia, the global warming potential is revealed as the most dominant criterion. The increase of this criterion weighting by 25% in case 4 perceptibly raised the similarity value of ammonia. This situation is directly related to ammonia's carbon-free structure.

5.4 Conclusions

The importance of reducing emissions from the maritime sector is growing every day. Using alternative marine fuels on ships offers excellent benefits for shipping companies in terms of reducing pollution. Furthermore, choosing the appropriate



	Base case	Equal weights	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
LNG d*	1.92	1.75	1.92	1.92	1.95	2.28	1.92	2.03	1.92
LNG d⁻	1.45	1.52	1.54	1.54	1.45	1.45	1.46	1.45	1.66
Methanol d*	1.51	1.41	1.54	1.51	1.55	1.77	1.51	1.51	1.58
Methanol d⁻	1.31	1.34	1.33	1.4	1.31	1.35	1.32	1.47	1.35
Ammonia d*	1.52	1.58	1.61	1.6	1.52	1.52	1.52	1.55	1.72
Ammonia d⁻	1.76	1.58	1.76	1.76	1.8	2.15	1.76	1.79	1.76
LNG Similarity	2.21	2.39	2.35	2.34	2.2	2.09	2.22	2.17	2.52
Methanol Similarity	2.18	2.3	2.19	2.33	2.15	2.11	2.19	2.44	2.21
Ammonia Similarity	2.92	2.58	2.86	2.86	2.98	3.56	2.92	2.94	2.79

Fig. 5.3 Results of sensitivity analysis

alternative fuel for both short-term and long-term investments may have significant benefits for the shipping industry.

In this study, a framework has been presented to determine the best alternative marine fuel option for marine vessels. LNG, methanol, and ammonia were considered throughout the analysis as alternative marine fuels. In the first part of the study, the stated fuels were analyzed by the SWOT analysis method. Thus, the advantages and disadvantages of these fuels have been identified. In addition, a process to determine the criteria that are important during the preference of alternative marine fuel use on board has been conducted with the SWOT analysis and research on the relevant literature. Within the scope of the methodology, safety, cost, exhaust emission, global warming potential, sustainability, storage, and technical competence were considered, and specified fuels were examined based on these criteria by the TOPSIS approach. Some marine professionals who work as marine engineers at various levels on board or academicians working in maritime education were asked to score criteria to conduct the analysis. The obtained judgments are analyzed, and the best option was determined. A sensitivity analysis was carried out to reveal the effect of the criterion weighting for the alternatives, and key findings were presented. The main outcomes of the study are as follows:

- Among the comparison criteria, the safety, global warming potential of the fuel, and its storage are found most important criteria.
- Among the fuel alternatives, ammonia is determined as the best alternative, while it is observed that LNG and methanol shared highly close similarity values as a result of the TOPSIS analysis.
- Although ammonia is a very promising fuel option for the maritime industry to eliminate ship-borne pollutants, there are some essential issues to be dealt with about its application.
- LNG has currently superiority within more technical competence, and the sector is familiar with its usage since complying with sulfur restrictions while methanol could be more adapted than its current status with a small arrangement in existing ships in the recent future.
- As a result of the sensitivity analysis, it is understood that the conducted analysis is very sensitive to the changing of C4.
- Within the scope of the study, a hybrid methodology that includes SWOT analysis and a multi-criteria decision-making approach is presented to determine the best alternative fuel option. Compared to the relevant literature, the inclusion of SWOT analysis in the methodology has strengthened the accuracy and effectiveness of the approach.
- For researchers interested in this field and maritime companies, the proposed methodology enables both firstly, to evaluate the advantages and disadvantageous sides of the alternatives within the SWOT analysis and secondly, to determine the best option according to the general intention of the expert consortium.

This study allows a beneficial framework for maritime companies to determine suitable alternative marine fuels for their ships in the fleet. On the other hand, the proposed methodology has a limitation in which it may be shaped according to the desire and intention of the expert consortium because it covers subjective judgments about the specified fuel options, comparison criteria, and their importance weights. In future studies, this study will extend by including more alternative marine fuel options and realizing analysis with various MCDM strategies. Also, we are planning to evaluate ammonia more deeply in future studies by considering ammonia fuel options such as those produced from natural gas or electrolysis based on renewable electricity and for use in fuel cells.

Appendix 5.1: SWOT Analysis of Marine Alternative Fuels

Types of fuels	Strengths	Weaknesses	Opportunities	Threats
LNG	• It reduces SO_x and PM emissions by 90–95% • It can reduce CO_2 emissions by approx. 25% • There are regulations for the use of LNG fuel • The reserve estimate is more than 250 years • It is cheaper than fossil fuels • It is non-explosive in a liquid state • It is not toxic • It is not corrosive • Safe gas operation	• It has a lower energy density than fuel oils • Larger volumes of LNG are required to produce the same energy content as conventional fuel oils • LNG storage tanks are usually located on outer surfaces on the deck • It does not singularly meet IMO's carbon reduction strategy	• There are two different types of engines: low pressure and high pressure • Otto and diesel processes can be applied • It can reduce operational costs • Flexible fuel changeovers can be made between fuel oil and LNG • The supply chain for bunkering is under development • Cost-effective clean fuel	• Methane slip • Boil-off
Methanol	• It has a lower carbon ratio than conventional fuels • It can reduce CO_2 emissions by approx. 25% • It provides an effective reduction in SOx and PM emissions due to the clean-burning properties of methanol • It has been approved by The IMO Maritime Safety Committee that it can be used as fuel on ships • It is easier to store and use on ships than other alternative fuels • It is liquid at ambient temperature	• It has a lower energy density than fuel oils • Larger volumes of methanol are required to produce the same energy content as conventional fuel oils • Exhaust treatment systems may be required to achieve IMO Tier III emission levels • It does not meet the IMO carbon reduction strategy singularly • It may be flammable when compared to others because its flammable range in the air is between 6% and 36.5% • Special fire extinguishing equipment should be used	• It can be used on ships by making minor modifications to existing systems • It has been used around the world for many years. Existing infrastructure can be modified to supply ports and ships • It can be easily stored with small arrangements to be made in the existing fuel tanks on the ships • It is currently considered the 4th most common marine fuel	• It is toxic and poisonous • Overexposure can cause death • It is corrosive to certain materials • Methanol vapor is heavier than air. For this reason, it may accumulate at points such as tank bottoms and pose a risk to seafarers

(continued)

(continued)

Types of fuels	Strengths	Weaknesses	Opportunities	Threats
Ammonia	• It proposes a zero-carbon emissions composition for the maritime industry • It meets IMO's initial GHG emission strategy • It can be stored as a liquid on ships at 20 °C and 8.6 bar (relatively higher temperature and lower pressure) • It has lower flammability when compared to others because its flammable range in air is between 15.15% and 27.35%	• Due to its structure, it requires a high proportion of pilot fuel for ignition • It has a lower energy density than fuel oils • Larger volumes of ammonia are required to produce the same energy content as petroleum-based fuels • For the safety of seafarers, exposure levels should be limited • It has poor combustion properties in internal combustion engines • SCR system can be installed to reduce NOx emissions • Fuel infrastructure for bunkering is insufficient • Fuel applications on ships are complex and have high costs compared to other systems	• The use of ammonia fuel is being developed for dual-fuel (DF) engines • It can be produced from fossil fuels using methods such as carbon capture or renewable energy	• It is considered a dangerous substance due to its toxic nature • Depending on the concentration exposed, it can irritate the eyes, lungs, and skin or be life-threatening by direct contact • The IGF code does not cover the use of NH_3 • It is not compatible with all materials due to its corrosive effect • Due to its characteristics, there is an increase in NOx emissions as a result of combustion in engines • It causes CO_2 release in global terms since the current production process is realized by HFO or coal

Sources Hansson et al. (2020), Xing et al. (2021), Wan et al. (2015), Chu et al. (2019), Gilbert et al. (2018), Alvela et al.(2018), Valera and Agarwal (2019;) ABS (2020a), Mallouppas and Yfantis (2021), Cheliotis et al. (2021), MAN Energy Solutions (2020), Ampah et al. (2021), Karatug et al. (2022), ABS (2021) ABS (2020b), Natural Resources Canada (2013), Salarkia and Golabi (2021)

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