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# Multicriteria Analysis of Alternative Marine Fuels in Sustainable Coastal Marine Traffic

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**Abstract:** Marine transportation is considered to be one of the most important aspects of global transportation services. Due to the increase in marine transportation, there are significant impacts on the marine environment. One of the possible measures for mitigation of the environmental impact could be switching to environmentally friendly fuel. However, the alternative fuel selection process is considered to be a problem due to various criteria to be considered and stakeholders that should be involved in the selection process. The aim of this paper is to demonstrate the application of multicriteria analysis as a decision-support tool for the alternative marine fuel selection problem in coastal marine traffic. The suggested methodology takes into account environmental, technological, and economic aspects, and ensures the participation of different stakeholders in the selection process. The priority ranking of the alternatives is based on a combination of the Analytic Hierarchy Process (AHP) and Simple Additive Weighting (SAW). The implementation of this method considers the involvement of relevant stakeholders through evaluation of the criteria weights and performance of each alternative with respect to each criterion. The method is applied for the case study of Croatia, where the results demonstrated that the best alternative for all stakeholders is electric propulsion, even though there are differences in opinions and perceptions with respect to the objectives and criteria. The findings of this analysis, likely the first of this type in this area, can serve as a solid basis for strategic planning.

**Keywords:** alternative marine fuel; sustainable coastal traffic; stakeholders; multicriteria analysis



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## 1. Introduction

Marine transportation is considered as one of the most important aspects of global transportation services. According to the Third International Maritime Organization (IMO) Greenhouse Gas Study [1], for the period 2007–2012, shipping emitted about 1000 million tons of $CO_2$ per year, equaling approximately 3.1% of the annual global $CO_2$ emissions. Maritime $CO_2$ emissions are projected to increase significantly in the coming decades, from 50% up to 250% by 2050. Annex VI to MARPOL, which entered into force in 2005, obliged manufacturers and shipping companies to follow the rules in ship design and manufacturing, as well as in marine traffic operations considering the air pollution from ships [2]. It is for certain that IMO and EU regulations will have an impact and cut sulfur emissions up to 2030. According to the current fuel consumption trends, in the absence of additional regulations, emissions from international shipping will grow further after 2030. In the coming decades, $SO_2$ emissions are expected to decrease by 50–80 percent, while the NOx emissions are expected to further increase and, shortly after 2030, they will reach levels that exceed the total land-based emissions in the EU-28 [3].

However, exhaust emissions from ships are not only an air pollution problem but they also cause significant impact on the underwater marine environment [4]. Various impacts of shipping on the marine environment can have significant and permanent consequences. Besides air pollution, they also include the possibility of oil spills, hazardous and noxious substances, sewage discharge and garbage, anti-fouling treatments, wrecks, invasive species, noise, as well as the cumulative effects of the above [5]. Due to $CO_2$ as well as $SO_2$ dissolution in the sea, which causes a decrease in seawater pH, acidification is constantly present in the marine environment [6,7]. According to the European Marine Strategy Framework Directive (MSFD), sea acidification is identified as a one of the most important issues to be considered in marine environment protection [8]. The main task of the MSFD is to achieve a Good Environmental Status (GES) of the marine environment within all member states, which involves the development of an overall plan of cost-effective and technically feasible measures for mitigation of different impacts on the marine environment [9,10].

Marine transport is considered as a catalyst for economic development in Europe, with over 400 million passengers embarking and disembarking at European ports [11]. Likewise, marine transportation is considered one of the most significant transport alternatives in Croatia. It is primarily established in order to connect major cities on the coastline with the surrounding islands, and it is related to the transport of passengers, cargo, and vehicles within internal waters and the territorial part of the Adriatic Sea [12]. It is constantly expanding considering the number of passengers and vehicles transferred each year. For instance, in the period between 2009 and 2019, the total number of passengers in the coastal liner services in Croatia has increased by more than 20% and the total number of vehicles increased up to 26%. Due to the intense marine activity along the coastline and increasing tourism, it can be expected that these number will continue to grow, resulting in a proportional environmental impact.

One of the possible measures for mitigation of the environmental impact coming from marine transport might be switching to an alternative fuel that is more acceptable for the environment. The aim of this paper is to demonstrate the application of multicriteria analysis as a decision-support tool for the alternative marine fuel selection problem in the Republic of Croatia. The multicriteria approach is employed for the alternative fuel selection process by defining the main goal of the analysis, and particular objectives and different criteria are applied to evaluate the performance of each alternative. The selection process considers environmental, technological, and economic aspects, which represent particular objectives of the multicriteria analysis. Ranking of alternatives is performed based on the combination of the Analytic Hierarchy Process (AHP) and Simple Additive Weighting (SAW), with representatives of all stakeholder groups participating in the selection process and avoiding potential conflicts. In order to demonstrate its application, an MCA model, which includes the objectives (environmental, economic, and technological) and criteria for alternative fuel selection, is built. Representatives from shipowners, acting as end-users, participated in the selection process along with representatives of the government. Furthermore, representatives of academia serving as neutral experts participated as well.

Application of the methodology and results are presented in Section 4. The hierarchical structure of the alternative fuel selection problem is presented in Section 4.1, which serves as a basis for the application of the multicriteria analysis. In the first step of the multicriteria analysis, participants expressed their preferences on the relative importance of each objective by assigning a relative degree of importance (Section 4.2). Furthermore, each objective consists of different criteria for which participants expressed opinions on their relative importance by assigning criteria weights. In the next step, participants evaluated the performances of the alternative marine fuels with respect to each criterion (Section 4.3). Finally, the ranking of fuel alternatives is performed by combining the performance score of each alternative in relation to each criterion, with respect to a particular criterion weight (Section 4.4).

## 2. Alternative Marine Fuel Selection Problem

A requirement for reduction of environmental impact from marine coastal traffic was a motivation to consider different mitigation measures. There are numerous studies proposing the methodology of evaluating the environmental impact from marine traffic as well as proposing different solutions. Trozzi and Vaccaro [13] described a methodology for estimation of air pollutant emissions from ships, showing that different emissions are present during cruising, maneuvering, and hoteling of ships. Panasiuk and Turkina [14] evaluated the installation of scrubbers as a solution for the reduction of SOx emissions in comparison to low sulfur fuel. Use of alternative fuels in marine transportation is recognized as one of the most effective solutions for mitigation of environmental impact. Hansson et al. [15] evaluated ammonia as a potential marine fuel to reduce the climate impact of shipping considering the short sea ships, deep sea ships, and container ships. Ren and Liang [16] compared alternative marine fuels by applying a fuzzy group approach, which was used to capture the opinions and preferences form different stakeholders. Deniz and Zincir [17] performed an environmental and economical assessment of alternative marine fuels. Hwang et al. [18] in their research performed a life-cycle assessment of a liquified natural gas (LNG)-fueled vessel in domestic services, focusing on the comparative analysis between LNG and conventional marine gas oil (MGO) and showing that the use of LNG can provide substantial benefits considering the environmental point of view. Still, this analysis considers marine transportation on a significantly long travel distance. In this paper, five alternative fuels were selected for the analysis. The general characteristics of each fuel, namely, the flash point, autoignition temperature, flammability limits, toxicity, and price levels, are provided in Table 1. Regarding biofuel, it is important to emphasize that this alternative fuel is considered in a general context; i.e., the exact type of biofuel was not specified for this research.

Environmental issues should be primarily considered at the strategic level of planning and decision making, in order to establish a framework for proper selection of mitigation measures and their implementation. Unfortunately, key maritime strategic document in Croatia, such as the Strategy of Maritime Development and Integrated Maritime Policy 2014–2020 [23], only superficially encompasses environmental issues. Any long-term planning with respect to marine environment protection and mitigation of environmental impact through reduction of acidification, for instance, is still not being considered. In 2016, the Republic of Croatia adopted the Act on the establishment of alternative fuel infrastructure [24]. Alternative fuels encompass electric energy, hydrogen, biofuel, natural gas (LNG), or liquefied petroleum gas (LPG). However, the elements of this Act considering the use of alternative fuels are not mandatory; they only provide a general framework on how to reduce the oil dependence in order to minimize the environmental impact in the future.

The latter shows that there are several unresolved issues in the legislative framework of Croatia considering application of alternative fuels, as well as a significant gap between the regulations and practical application. The Adriatic Sea, being one of the most vulnerable of the European seas according to the MSFD [8], requires appropriate strategies as well as policies to preserve its natural biodiversity and to maintain the sustainable development of the marine environment and coastal area. One of the potential solutions could be switching to more environmentally friendly fuel alternatives for coastal transportation. Use of environmentally friendly fuel in coastal marine traffic could certainly contribute to sustainable traffic development by reducing greenhouse gas and other emissions.

However, the question remains on how to select the alternative marine fuel for particular use in coastal transportation. Extensive research regarding assessment of marine fuels has been carried out. The authors in [25], by searching Scopus, illustrated in their work which type of aspect is mostly used in assessment of marine fuels. The majority of the assessments considered the environmental aspects and emissions, while economic aspect also has increased. Selection of alternative marine fuel should consider different aspects, other than just environmental. A selected alternative should be cost-effective, allowing end-users to sustain their activities from an economic point of view. Development of policies considering the selection and use of alternative fuel should be based on a compromise in opinions between the government and end-users, meaning that both groups should participate in the selection process.

**Table 1.** Overview of the alternative fuel characteristics analyzed in research.

| Fuel | Description/Characteristics | Flash Point (°C) | Autoignition Temperature (°C) | Flammability Limits (Volume % in Air) | Toxicity | National Average Price * |
|---|---|---|---|---|---|---|
| **Biofuels** | Derived from primary biomass or biomass residues that are converted into liquid or gaseous fuels. The most promising biofuels for ships: biodiesel (e.g., HVO—hydrotreated vegetable oil, BTL–biomass-to-liquids, FAME–fatty acid methyl ester), and LBG (liquid biogas, which primarily consist of methane). | For HVO: >61 | 204 | Approx. 0.6–7.5 | Not toxic | ** Biodiesel (B20): 2.29 $/gallon |
| **LNG** | The hydro-carbon fuel with the lowest carbon content and highest potential for reduction of CO2. Main component: methane (CH4). | −188 | 537 | 4–15 | Not toxic | ** 2.72 $/DGE (per Diesel Gallon Equivalent) |
| **Hydrogen** | Hydrogen (H2) can be produced in several different ways, for example by electrolysis of renewable matter or by reforming natural gas. The production of hydrogen through electrolysis could be combined with the growing renewable energy sector which delivers, by its nature, intermittent power only. | Not defined | 500 | 4–74.2 | Not toxic | n/a |
| **LPG** | Liquefied petroleum gas (LPG) is by definition any mixture of propane and butane in liquid form. Mixing butane and propane enables specific saturation pressure and temperature characteristics. | −104 | 410–580 (depending on the composition) | 1.8–10.1 | Not toxic | * 0.65 $/per liter |
| **Batteries** | Batteries provide the ability to directly store electrical energy for propulsion, opening up many other opportunities to optimize the power system. | n/a | n/a | n/a | n/a | * 0.124 $/kWh |

* Prices on 15 February 2021. Global Petrol Prices [19]. ** Prices according the Alternative Fuel Price Report (average prices between October 1 and 15) [20]. Sources: Prepared by authors using [19–22].

Omitting the end-users from the decision-making process could lead to potential conflict due to possible imposition of a certain solution from the government. Still, there is a requirement for a convenient method for the stakeholders to express their opinions and preferences on the relative importance of the criteria and the relative performances on the alternative marine fuels with respect to each criterion [16].

In Figure 1, a scheme describing an alternative marine fuel selection problem is presented. The selection process starts with the identification of the problem followed by the definition of the available alternatives and criteria for evaluation of each alternative. Furthermore, the relevant stakeholders that are going to be included in the selection process are defined. Participation of different stakeholders is required in order to determine the particular weights of each criteria and to avoid potential conflicts during the selection process. Once the criteria weights are determined, an evaluation of the performance of each alternative is performed with respect to each criterion. During the evaluation of each alternative, the data about its performance is required in order to perform the relative ranking of the alternatives. However, if the data about the particular performance is not available, the only solution is to rely on the stakeholders' evaluation of the alternatives. Once the data about the performance of each alternative is collected, the final ranking of alternatives is performed, completing the fuel selection process.

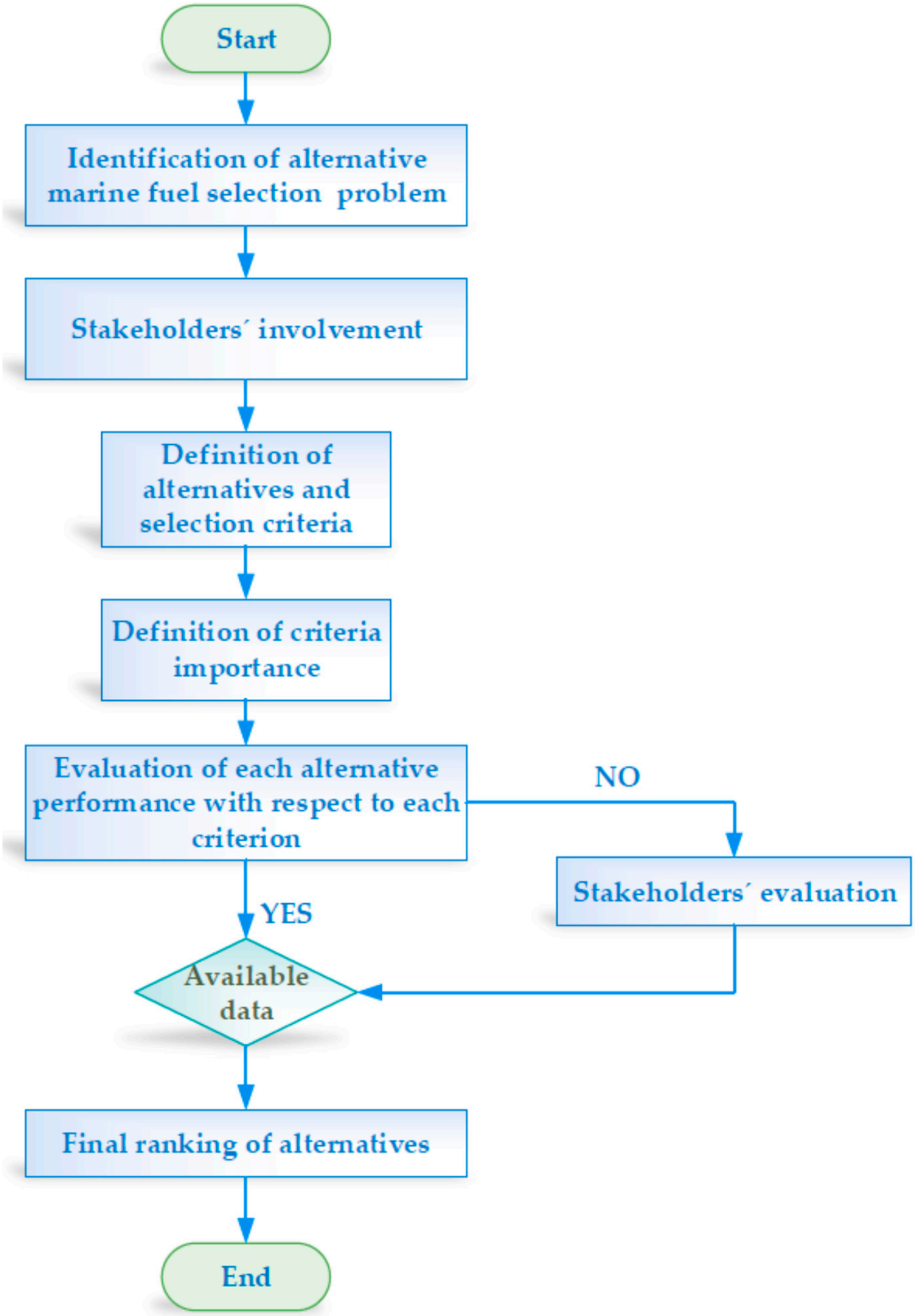


**Figure 1.** Alternative marine fuel selection problem.

Despite the fact that alternative fuels are widely considered as a feasible option for mitigation of environmental impact, wider implementation in coastal liner transportation is still missing. Furthermore, the list of alternative fuels analyzed in the reviewed literature [15–18] is slightly different from the alternatives encompassed in the Croatian Act on the establishment of alternative fuel infrastructure [24]. Considering the research on environmental impact from shipping in Croatia, Runko Luttenberger et al. [26] provided a study concerning the sustainability of coastal traffic in Croatia, which analyzed the advantages of short sea shipping (SSS) in Croatia as well as the environmental concerns related to shipping in general and short sea shipping in particular. The potential to reduce environmental pollution from ships through a modular concept approach was presented in [27], while a comparative life-cycle assessment of a battery and diesel engine-driven ro-ro passenger vessel was provided in [28]. Considering an alternative fuel application in marine transportation in Croatia, Perčić et al. [29] performed a life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short sea shipping.

## 3. Materials and Methods

The study area selected for the analysis is Croatia, which represents a Mediterranean country with a significant use of marine transportation. Pressure on the marine environment is significantly growing and proportional to the increase in passengers in marine transportation. Furthermore, many ships that are currently used in Croatian marine transport are technologically obsolete. Still, replacement of the coastal transportation fleet is currently not a feasible option. The selected strategy for environmental impact mitigation must be feasible considering the technological requirements as well as economic planning. Therefore, we propose a multicriteria approach for the evaluation of fuel alternatives, allowing inclusion of different objectives and criteria during the evaluation of alternatives.

### *3.1. Study Area*

Total length of the Croatian coastline is approximately 6000 km, with islands and islets included. Economic and social development are dependent on coastal marine traffic, which provides frequent connections between the major coastal cities and majority of islands. This is particularly important during the summer, with over 20 million tourists visiting Croatia in 2019. Coastal marine traffic in Croatia connects 73 islands and 22 mainland ports, operating 24 ferry, 15 high-speed, and 13 shipping liner services (52 national lines in total). A combined fleet of over 70 ships provided by 14 Croatian shipping companies is responsible for coastal marine traffic service. Croatia, like many other Mediterranean countries, faces a significant growth in marine transportation. In Table 2, a comparison between Croatia, Greece, Italy, and Spain is shown, where it can be seen that the total number of passengers in 2019 is almost equal to Spain [30]. Considering the number of inhabitants of each country, the ratio between the total number of passengers and inhabitants is shown in the last column, where it can be seen that Croatia has the highest value.

**Table 2.** Comparison between Mediterranean countries in total number of passengers and ratio of passengers per inhabitant [30].

| Country | Total Number of Passengers | Passengers per Inhabitant Ratio |
|---|---|---|
| Croatia | 34,142,000 | 8.37 |
| Greece | 86,530,000 | 1.43 |
| Italy | 73,930,000 | 6.89 |
| Spain | 34,635,000 | 0.73 |

The Intergovernmental Panel on Climate Change (IPCC, Geneva, Switzerland) reported that the vast majority of marine propulsion and auxiliary plants on board ocean-going ships are diesel engines, which typically have service lives of 30 years or more. Thus, the IPCC concluded that it will be a long time before technical measures can be implemented in the fleet on any significant scale [31]. A similar situation currently prevails in coastal transportation in Croatia, where ships are mostly equipped with diesel engines. In Figure 2, we showed that the average ship age in Croatia is equal to 30 years, and more than 50% of the ships are more than 30 years old.

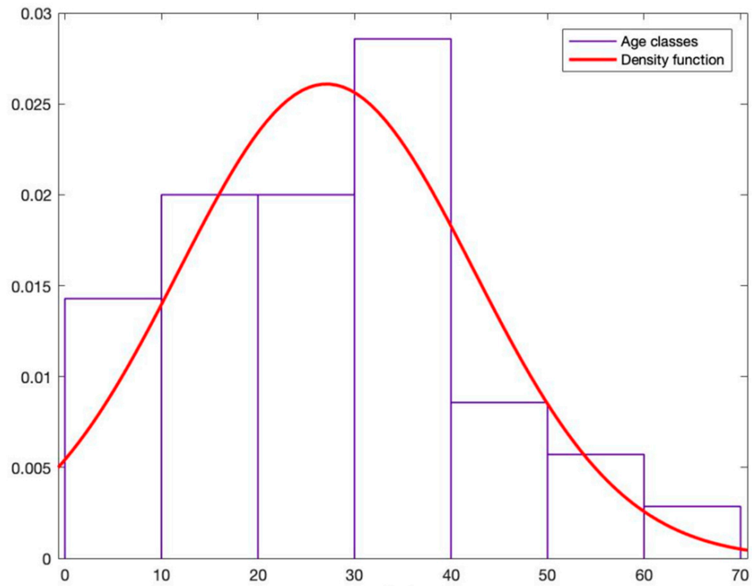


**Figure 2.** Average ship age distribution in Croatia. Source: Prepared by authors using data provided by [32].

Annex VI to MARPOL, which entered into force in 2005, enacted international legislation related to air pollution from ships and obliged manufacturers and shipping companies to follow the rules stated in Annex VI with regard to ship design and manufacturing, as well as in marine traffic operations. However, most of the ships have been built before the enforcement of Annex VI of MARPOL and it is impossible to modernize or replace the ship fleet instantly and thus ensure marine fuel replacement as an acceptable alternative in satisfying the goals stated in Annex VI and other relevant legal documents.

Considering fuel consumption, which is considered to be one of the most significant factors when analyzing the environmental impact of ships through exhaust emissions, Figure 3 presents the analyzed data on age and consumption ratio. It can be seen that a lower fuel consumption is not proportional to decreasing age. This could be misleading since a lower fuel consumption can be the result of a lower gross tonnage in comparison to newer ships. Furthermore, modern engines are improved in terms of satisfying the allowed exhaust emission limits.

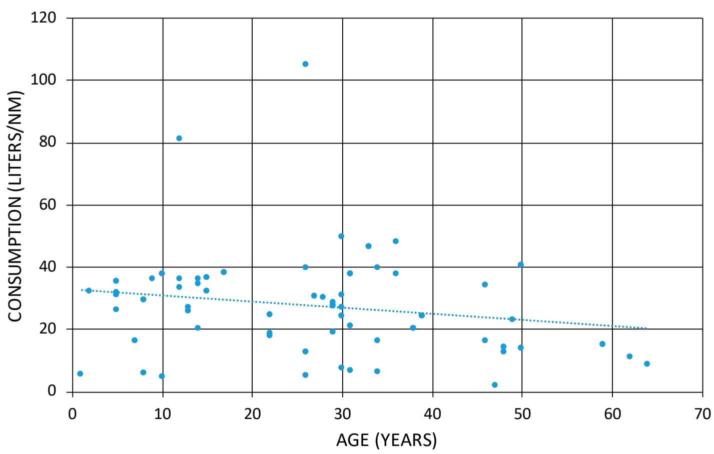


**Figure 3.** The age–consumption ratio of coastal line ships in the Republic of Croatia. Source: Prepared by authors using data provided by [32].

Expanding marine transportation in Croatia was a motivation to consider the implementation of alternative fuel as an environmental impact mitigation measure. Use of alternative fuels in coastal marine traffic could certainly contribute to sustainable development of the marine environment and coastal area. However, different aspects should be considered during selection of an appropriate marine fuel alternative. In Croatia, the Coastal Liner Shipping Agency represents a governmental regulatory body, which is in charge of defining particular conditions for granting marine transportation lines to shipping companies. Furthermore, out of 14 shipping companies currently providing traffic services in the coastal area, only one shipping company is under state ownership (the largest one) and it is run by governmental authorities, while the remaining 13 are privately owned. We believe that decision making at the governmental level only could lead to potential conflict since shipowners are not included in the decision process. This was a reason to expand the list of participating stakeholders, in order to record their particular opinions and preferences as well as to identify potential differences.

### 3.2. The Application of Multicriteria Approach

Multicriteria decision analysis (MCDA) is a method that is broadly used in order to solve complex problems, which are often consist of contradictory criteria and different quantitative and qualitative measures [33,34]. The authors in [35] defined MCDA as an "umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter".

Due to the fact that the process of alternative marine fuel selection considers multiple aspects and the involvement of different stakeholders, we decided to apply the multicriteria approach. It is widely used when analyzing complex tasks and it found its application in many different fields, such as marine spatial data infrastructure [36], decision support to policy selection [37], energy issues and sustainable development of the energy supply systems [38,39], and urban road infrastructure maintenance planning [40]. This approach has already been used for marine fuels [17,41].

The authors in [41], by applying MCDA, assessed the prospects for seven alternative fuels, including biofuels. In their assessment, various groups of Swedish stakeholders were involved (industry representatives from shipowners, fuel producers, government authorities, and engine manufacturers). The ranked criteria cover four aspects: economic, environmental, technical, and social. Their results showed that different stakeholders have different priorities. From a government perspective, the most important criterion is the environment, while industry representatives ranked economic criteria as the most important.

The multicriteria decision analysis process is based on several steps: In the first step, a decision problem is defined along with the main goal. In the second step, a set of objectives and corresponding criteria is defined. The objectives and criteria are assigned with weights representing their degree of importance. A set of alternatives is defined in the further step, and values representing their particular performance are attributed to each criterion and goal. Finally, alternatives are ranked according to their overall performance. It is important to highlight that the purpose of the multicriteria analysis is to provide support during the decision-making process, rather than choosing only one solution. According to the stakeholder's interests, any new criteria for evaluation of alternatives may be added and appraised through the multicriteria analysis method.

The Analytic Hierarchy Process (AHP), one of the most widely used multicriteria decision-making tools developed by Saaty [42], is used for assigning weights to elements at each level of the hierarchy, in order to define and prioritize key elements in the evaluation of each alternative. Elements of each level are compared to each other using a pairwise comparison, creating a comparison matrix with a range depending on the number of elements at each level. In order to define the matrix, pairwise comparisons can be translated into scale values where the preferences of the decision makers are expressed through Saaty's nine-point ranking scale, S = (1, 2, 3, 4,5, 6, 7, 9), used to describe the intensity of the mutual relationship from equal to extreme. Values 1, 3, 5, 7, and 9 represent the main scoring values, and 2, 4, 6, and 8 represent intermediate values. After defining the matrix of pairwise comparisons, the vector of relative weight is estimated. The validity of the comparisons is evaluated by calculating the consistency ratio (CR):

$$CR = \frac{CI}{RI} \quad (1)$$

where RI is the random consistency index and CI is the consistency index defined as CI = $(\lambda_{max} - n)/(n-1)$, where $\lambda_{max}$ is the maximum eigenvalue.

Once the criteria and corresponding weights are determined, the performance of each alternative is evaluated in comparison to all criteria and objectives. The performance of the alternatives is evaluated using the Simple Additive Weighting (SAW) method, which is also known as the weighted linear combination, or weighted summing method. The concept of the SAW method is based on calculating the evaluation score, which is a weighted sum of the performance ratings of each alternative in comparison to all attributes. The evaluation score is calculated for each alternative by multiplying the scaled value ascribed to the alternative of that attribute with the assigned criteria weights followed by summing of the products for all criteria. The rating values in the decision matrix must be normalized in order to be mutually comparable. The normalization procedure is based on the following expressions, depending on if the desired goal is the maximization or minimization of a particular score:

$$\begin{aligned} x_{ij} &= \frac{r_{ij}}{r_{max}} \\ x_{ij} &= \frac{r_{min}}{r_{ij}} \end{aligned} \quad (2)$$

where $x_{ij}$ is the score of the *i*-th alternative with respect to the *j*-th criteria, $r_{ij}$ is equal to the relative score, and $r_{max}$ and $r_{min}$ are the maximum and minimum numbers, respectively. Each alternative is then evaluated using the following formula:

$$A_i = \sum_{j=1}^{n} w_j \times x_{ij} \quad (3)$$

where $A_i$ is *i*-th alternative, $x_{ij}$ is the score of the *i*-th alternative with respect to the *j*-th criteria, and $w_j$ is the weighted criteria.

## 4. Application and Analysis of the Results

Sustainability of marine transportation can be achieved only if all relevant aspects are taken into consideration. In this section, a multicriteria approach is applied on the alternative fuel selection problem considering the particular requirements of Croatia. Fuel alternatives are selected according to Croatian Act on the establishment of alternative fuel infrastructure [24], and representatives from shipowners, government, and academia participated in the selection process. In the first step of the analysis, the research problem is structured consisting of the main goal, particular objectives, criteria, and alternatives. In the second step, participants evaluated the importance of each particular objective followed by the evaluation of criteria importance. Furthermore, the performance of each alternative was evaluated with respect to each criterion. In the last step, the final ranking of all alternatives was performed, considering each stakeholder group involved in the analysis.

### *4.1. Application of Multicriteria Approach for Alternative Fuel Selection*

The alternative fuel selection problem is represented in a hierarchical form with four levels, in order to facilitate the structure of the problem. We propose a hierarchical structure (Figure 4) starting with the main goal at the top—that being the achievement of sustainable marine coastal traffic. The main goal is supported by three objectives that need to be accomplished in order to achieve such a goal. In this way, we managed to reduce the degree of the complexity in the further analyses by separating the main goal and particular objectives. Those objectives are (a) "maximization of environmental aspects", (b) "maximization of technological aspects", and (c) "maximization of economic aspects".

Each of the three objectives is divided into supporting or sub-objectives, representing criteria for evaluation of the alternatives. Objective (a) is supported by three sub-objectives, objective (b) by four sub-objectives, and objective (c) by three sub-objectives. Alternatives are placed at the bottom of the structure and they are connected to all criteria groups, meaning that their evaluation considers the maximum utilization of all objectives.

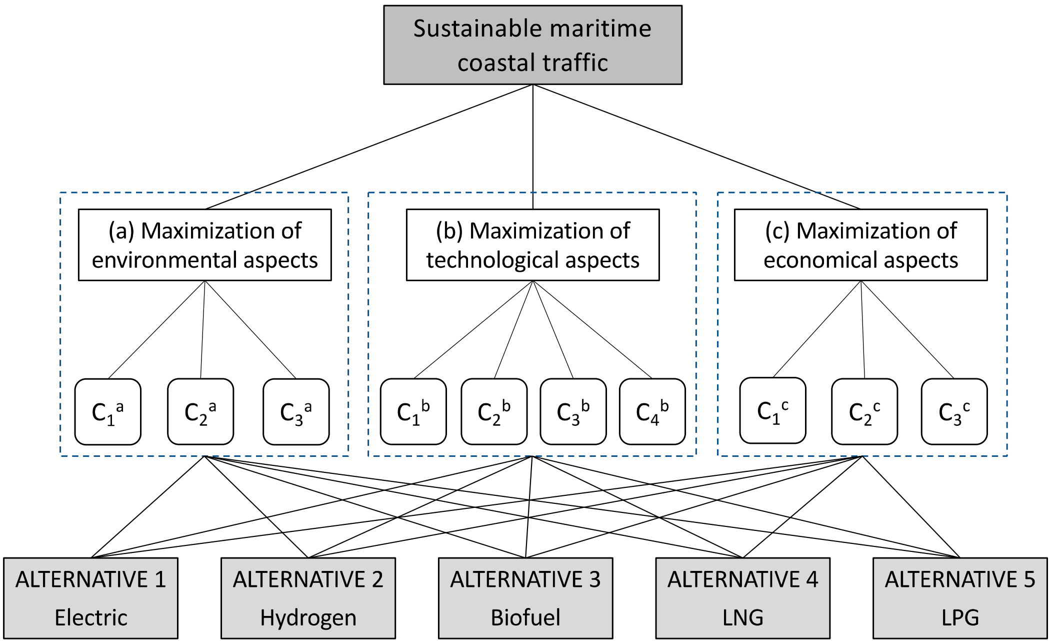


**Figure 4.** Hierarchical structure of the alternative fuel selection problem.

The criteria chosen for the analysis consider the environmental, technological, and economic aspects. Each selected aspect consists of several criteria (shown in Table 3) and is further evaluated by the stakeholders. The selection of these particular criteria, however, was based on the combination of similar research [16,25,41,43] and discussion with stakeholders. The result is 10 criteria in total (three are related to environmental, four to technological, and three to economic aspects). The environmental criteria consider climate change impact from marine coastal traffic through global warming potential, acidification of the sea due to $CO_2$ dissolvement, and exhaust emissions considering the air quality in the vicinity of marine transport routes and potential health impact. The technological criteria consider the existence and availability of alternative fuel-related infrastructure, the reliability of fuel supply, possibility and requirements for adaptation of ship engines to alternative fuel, and the safety of the alternative in terms of general use. The economic criteria consider the required investment size due to new technological requirements, operational costs considering the requirement for possible additional personnel or crew, maintenance or insurance policies, and the last criterion is the fuel purchase price.

Following the hierarchical scheme presented in Figure 4, the importance of each main objective is evaluated followed by the evaluation of the sub-objectives or criteria. The evaluation is based on a questionnaire that was presented to each stakeholder and their task was to estimate the relative importance of each element within every group. A comparison matrix was created based on the pairwise comparison data, and the overall criteria weights were determined based on the AHP methodology.

In the second part of the evaluation, stakeholders evaluated the performance of each alternative in relation to every sub-objective or criterion. Alternatives are selected according to Act on the establishment of alternative fuel infrastructure [13]. The evaluation of the performance is based on the stakeholders' knowledge, opinions, and experience. The performance of all criteria was evaluated on an absolute scale and using the SAW approach the results were normalized and implemented into the final ranking results.

**Table 3.** Selected criteria for each criteria group.

| Group | Criteria |
|---|---|
| Environmental | Climate change impact $C_1{}^a$<br>Acidification $C_2{}^a$<br>Exhaust emissions $C_3{}^a$ |
| Technological | Available infrastructure $C_1{}^b$<br>Reliability of supply $C_2{}^b$<br>Adaptation of ship engines $C_3{}^b$<br>Safety of fuel $C_4{}^b$ |
| Economical | Investment $C_1{}^c$<br>Operational cost $C_2{}^c$<br>Fuel price $C_3{}^c$ |

### *4.2. Definition of Objectives Importance and Criteria Weights*

In the first step, the main objectives from the hierarchical scheme are evaluated from the stakeholders' perspective. A total of 20 participants joined the survey, of which eight represented shipowners, six represented the government, and six represented academia. It involved the importance evaluation of the environmental, technological, and economical objectives; these results are presented in Figure 5. The objectives were evaluated on a relative scale, showing that representatives from shipowners consider economic objectives as the most important and environmental aspects the least. Representatives from the government consider economic aspects as the most important, with a significant difference compared to the other aspects. On the other hand, representatives from academia consider the environmental aspects as the most important.

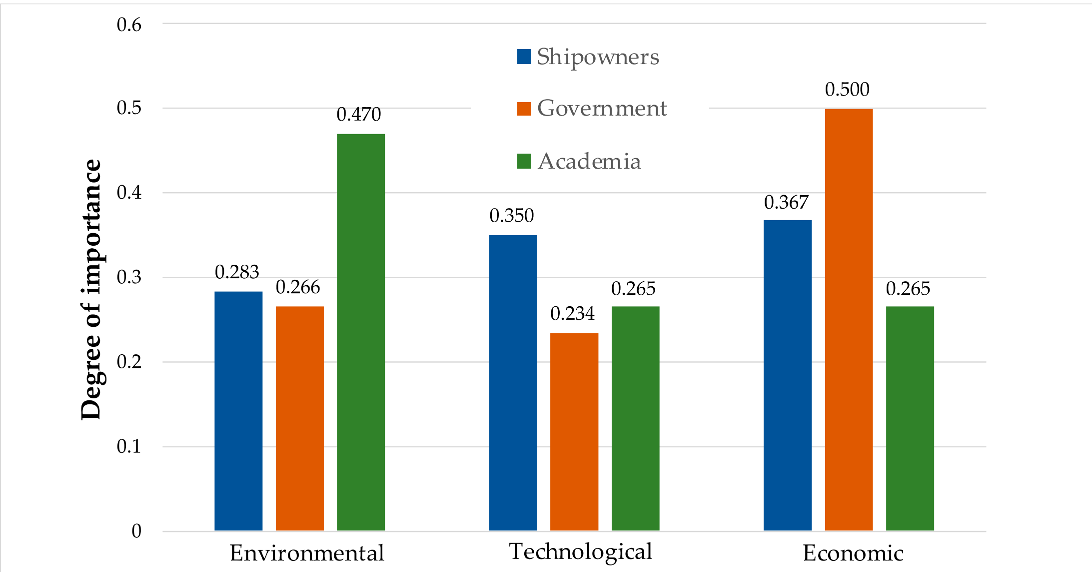


**Figure 5.** Definition of importance of the different objectives.

In the next step, criteria representing the supporting sub-objectives for each objective group were evaluated by the included stakeholders. Although there were 10 criteria proposed for evaluation, by separating the criteria into particular groups the authors managed to reduce the level of complexity, not only to ensure that the consistency ratio remains within accepted range but also to facilitate the comparison process. The evaluation was performed using the Saaty 9-point scale and the normalized results are listed in Table 4, where it can be seen that certain differences between the stakeholders' evaluation do exist.

**Table 4.** Overview of the evaluation of criteria importance by three groups of stakeholders.

| Criteria | Shipowners | Government | Academia |
|---|---|---|---|
| Climate change impact $C_1{}^a$ | 0.367 | 0.333 | 0.346 |
| Acidification $C_2{}^a$ | 0.300 | 0.333 | 0.308 |
| Exhaust emissions $C_3{}^a$ | 0.333 | 0.333 | 0.346 |
| Available infrastructure $C_1{}^b$ | 0.273 | 0.242 | 0.237 |
| Reliability of supply $C_2{}^b$ | 0.273 | 0.242 | 0.237 |
| Adaptation of ship engines $C_3{}^b$ | 0.204 | 0.242 | 0.263 |
| Safety of fuel $C_4{}^b$ | 0.250 | 0.274 | 0.263 |
| Investment $C_1{}^c$ | 0.294 | 0.310 | 0.345 |
| Operational cost $C_2{}^c$ | 0.294 | 0.345 | 0.310 |
| Fuel price $C_3{}^c$ | 0.412 | 0.345 | 0.345 |

Finally, the overall results of the criteria weight evaluation are presented in Table 5. These values represent the product of the degree of importance for each objective (shown in Figure 5), and the evaluation results are shown in Table 4. It can be seen that there are significant differences in the results. According to the shipowners, the criterion with the highest score is $C_3{}^C$, "Fuel price", while criterion $C_3{}^b$, "Adaptation of ship engines", has the lowest score. It is interesting to note that criterion $C_1{}^a$, "Climate change impact", has a relatively high score along with criteria from the economic group. Considering the stakeholders from the government, there is a difference between the scores, with the economic criteria having a significantly higher score in comparison to the other groups, and the technological group of criteria was evaluated as the least important with a more than three times lower score. This is a result of the significant difference in evaluation of the main objectives (Figure 5). Stakeholders from academia evaluated environmental criteria as the most important in comparison to other groups, with "Climate change impact" marked as the most important criterion. In the last column, the average criteria weights scenario is presented based on the average value of the previously estimated weights, where the highest value is related to $C_3{}^C$, "Fuel price", while the lowest score is related to the "Adaptation of ship engines" criterion.

**Table 5.** Overview of the results of the normalized criteria weights obtained from three groups of stakeholders.

| Criteria | Shipowners | Government | Academia | Average |
|---|---|---|---|---|
| Climate change impact $C_1{}^a$ | 0.1039 | 0.0886 | 0.1626 | 0.1184 |
| Acidification $C_2{}^a$ | 0.0849 | 0.0886 | 0.1448 | 0.1061 |
| Exhaust emissions $C_3{}^a$ | 0.0941 | 0.0886 | 0.1626 | 0.1151 |
| Available infrastructure $C_1{}^b$ | 0.0956 | 0.0566 | 0.0628 | 0.0717 |
| Reliability of supply $C_2{}^b$ | 0.0956 | 0.0566 | 0.0628 | 0.0717 |
| Adaptation of ship engines $C_3{}^b$ | 0.0714 | 0.0566 | 0.0697 | 0.0659 |
| Safety of fuel $C_4{}^b$ | 0.0875 | 0.0643 | 0.0697 | 0.0738 |
| Investment $C_1{}^c$ | 0.1079 | 0.1551 | 0.0914 | 0.1181 |
| Operational cost $C_2{}^c$ | 0.1079 | 0.1725 | 0.0822 | 0.1209 |
| Fuel price $C_3{}^c$ | 0.1512 | 0.1725 | 0.0914 | 0.1384 |

### *4.3. Definition of Alternatives Performance Score*

In the second step of the evaluation, the alternatives were ranked according to their particular scores and criteria weights. Stakeholders were requested to evaluate alternatives in comparison to all criteria. The evaluation was performed by assigning each alternative an absolute value score (0–10), which reflects their perception and experience on how each alternative satisfies a particular criterion. During the evaluation, stakeholders were encouraged to combine their knowledge with the available literature and other materials. Due to a general lack of data in Croatia, the final results were a combination of expert judgement and data from specific research or other relevant materials.

The first part of the ranking procedure was to analyze the particular scope of each criterion, since the maximum or minimum can be their target values. In Table 6, a list of criteria is presented along with the particular scope, based on which the particular normalization (2) is applied to the results.

**Table 6.** List of criteria with their priority target.

| Criteria | Target |
|---|---|
| Climate change impact $C_1^a$ | Minimization |
| Acidification $C_2^a$ | Minimization |
| Exhaust emissions $C_3^a$ | Minimization |
| Available infrastructure $C_1^b$ | Maximization |
| Reliability of supply $C_2^b$ | Maximization |
| Adaptation of ship engines $C_3^b$ | Minimization |
| Safety of fuel $C_4^b$ | Maximization |
| Investment $C_1^c$ | Minimization |
| Operational cost $C_2^c$ | Minimization |
| Fuel price $C_3^c$ | Minimization |

The performance of each alternative is evaluated by all participants on an absolute scale of 0–10. Once all alternatives are evaluated, their scores are set to relative values by performing the normalization procedure where values are compared to the maximum and minimum recorded values, respectively. In Table 7, the results of the evaluation of each alternative are presented considering the shipowners', government's, and academics' perspective. It is interesting to note that the electric alternative scored the highest score in relation to six criteria, while hydrogen and LNG scored the highest score in relation one, respectively. Considering the climate change impact, the electric alternative scored the highest score followed by hydrogen and biofuel, while LNG got the lowest score. Considering the acidification, the results are pretty much similar to previous ones. Exhaust emissions are considered lowest from the hydrogen use but all alternatives have a relatively solid score. The available infrastructure is considered the best for the electric alternative, while hydrogen and biofuel are considered the worst. Similarly, reliability of supply is the best for the electric alternative. Considering the adaptation of ships' engines, it is interesting to note that all alternatives achieved a very high score with hydrogen being the best. Safety of fuel is considered highest for the electric alternative, followed by hydrogen and biofuel. Investment cost is considered lowest for the electric alternative. However, considering operational costs and fuel price, the LNG and LPG alternatives were two of the best.

**Table 7.** Evaluation of the alternatives' performance as obtained from the shipowners' (S), government's (G), and academics' (A) perspective.

| Criteria | Electric | | | Hydrogen | | | Biofuel | | | LNG | | | LPG | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **S** | **G** | **A** | **S** | **G** | **A** | **S** | **G** | **A** | **S** | **G** | **A** | **S** | **G** | **A** |
| $C_1^a$ | 1.000 | 0.831 | 0.958 | 0.949 | 1.000 | 1.000 | 0.888 | 0.706 | 0.696 | 0.324 | 0.725 | 0.674 | 0.615 | 0.636 | 0.651 |
| $C_2^a$ | 1.000 | 0.974 | 1.000 | 0.952 | 1.000 | 0.968 | 0.976 | 0.794 | 0.766 | 0.348 | 0.651 | 0.533 | 0.597 | 0.638 | 0.551 |
| $C_3^a$ | 0.892 | 0.947 | 0.947 | 1.000 | 1.000 | 1.000 | 0.776 | 0.786 | 0.633 | 0.682 | 0.621 | 0.535 | 0.639 | 0.595 | 0.557 |
| $C_1^b$ | 1.000 | 0.823 | 0.467 | 0.364 | 0.355 | 0.687 | 0.335 | 0.693 | 0.418 | 0.770 | 0.993 | 1.000 | 0.691 | 1.000 | 0.967 |
| $C_2^b$ | 1.000 | 1.000 | 1.000 | 0.370 | 0.451 | 0.788 | 0.461 | 0.272 | 0.497 | 0.806 | 0.975 | 0.977 | 0.838 | 0.940 | 0.977 |
| $C_3^b$ | 0.927 | 0.583 | 0.551 | 1.000 | 0.378 | 0.525 | 0.925 | 0.805 | 0.896 | 0.862 | 1.000 | 1.000 | 0.993 | 0.964 | 0.956 |
| $C_4^b$ | 1.000 | 0.968 | 0.979 | 0.826 | 1.000 | 1.000 | 0.884 | 0.722 | 0.661 | 0.490 | 0.484 | 0.374 | 0.512 | 0.496 | 0.354 |
| $C_1^c$ | 1.000 | 0.741 | 0.668 | 0.893 | 0.595 | 0.607 | 0.872 | 0.786 | 0.709 | 0.767 | 1.000 | 1.000 | 0.813 | 0.985 | 0.950 |
| $C_2^c$ | 0.768 | 0.838 | 0.998 | 0.619 | 0.978 | 0.808 | 0.806 | 0.874 | 0.908 | 0.892 | 1.000 | 1.000 | 1.000 | 0.977 | 0.984 |
| $C_3^c$ | 0.983 | 1.000 | 0.976 | 0.581 | 0.954 | 1.000 | 0.435 | 0.537 | 0.471 | 1.000 | 0.856 | 0.730 | 0.953 | 0.918 | 0.684 |

Considering the stakeholders from government, the highest score in most categories is recorded for hydrogen—for four criteria. However, other alternatives such as LNG scored the maximum score for three criteria, electric for two, and LPG scored the maximum score for one. Climate change, acidification, and exhaust emissions were evaluated as lowest considering the hydrogen alternative. The electric alternative scored high scores as well regarding the environmental criteria. Considering the available infrastructure, LPG and LNG scored the highest score while hydrogen has a notably lower score. Considering the reliability of supply, the electric alternative got the highest score, followed by LNG and LPG. Adaptation of engines provided the highest score for LNG and LPG again, while safety of the fuel provided totally opposite results. Considering the economic criteria, LNG and LPG got the best overall score. There are differences between the alternatives considering the investment cost, while the scores related to operational costs and fuel price are similar.

Regarding the representatives from academia, hydrogen and LNG scored the highest score in four categories, while electric scored the highest score in two categories. Considering the environmental criteria, the electric and hydrogen alternatives scored the highest score with respect to all three criteria. Regarding the technological criteria, the available infrastructure is considered the best for the LNG and LPG alternatives, and the reliability of supply is considered highest for the electric, LNG, and LPG alternatives, which scored the highest score related to adaptation of engines. Safety of fuel is considered highest for the hydrogen and electric alternatives, while LNG and LPG are considered the least safe. The required investment is considered lowest for LNG and LPG, the operational costs are estimated to be similar for all alternatives, and the fuel price is considered lowest for the hydrogen and electric alternatives.

### 4.4. Ranking of Alternatives

Table 8 presents the final ranking of all alternatives from the shipowners', government's, and academia's perspective, as well as the compromise scenario based on the average value of the criteria weights and average score. As can be seen in Table 8, there are differences in final ranking considering the stakeholders' perception. According to the shipowners, the highest-ranked alternative fuel is electric, and the lowest is LNG. Regarding the government, the electric alternative has the highest ranking as well; however, the differences between the other alternatives are small, except for biofuel. Finally, according to the stakeholders from academia, the highest ranking is given to the electric alternative as well, showing that all stakeholders have agreed on the selection of the best alternative. What is in common to all involved stakeholders is that biofuel mostly has a very low score. Since the analyses of all stakeholders resulted in an identical alternative, a compromise scenario was not considered in the final ranking of the alternatives.

**Table 8.** Final ranking of the alternatives.

| | Shipowners | Government | Academia |
|---|---|---|---|
| **Electric** | 0.9571 | 0.8743 | 0.8857 |
| **Hydrogen** | 0.7384 | 0.8227 | 0.8776 |
| **Biofuel** | 0.7145 | 0.7144 | 0.6754 |
| **LNG** | 0.7126 | 0.8514 | 0.7339 |
| **LPG** | 0.7763 | 0.8416 | 0.7199 |

## 5. Discussion and Conclusions

The problem of selecting the best solution during the selection of alternative marine fuels is very complex since all criteria and conditions, which include geographical, ecological, economic, technical, technological, and social aspects, should be thoroughly considered. In this paper, an approach for selection of alternative marine fuel as a measure for mitigation of environmental impact for the case study of Croatia is presented. The selection process was performed using a multicriteria approach with different objectives and criteria used for the evaluation of the alternatives.

Defining the importance of each objective group and giving the appropriate weighting of the criteria representing the supporting sub-objectives for the selection of alternative marine fuel were done on the basis of the information obtained from three groups of stakeholders (shipowners, government, and academia). Furthermore, participants evaluated the performance of each alternative in relation to each criterion. The priority ranking of alternatives was based on the combination of the Analytic Hierarchy Process (AHP) and Simple Additive Weighting (SAW), resulting in a final ranking of all alternatives, whereby electric propulsion was considered the best option among all stakeholders.

Although the evaluation process showed significant differences, the final result of the analysis showed a common agreement between the stakeholders about the best alternative. It is important to note that all participants that took part in the decision-making process were introduced with the limitations of the methodology before expressing their attitudes and opinions. Mutual consent and approval of the stakeholders' different attitudes is crucial in this kind of analyses, since it guarantees the acceptance of the compromise results between all stakeholders. By applying the proposed concept, a holistic approach is applied in the decision-making process by involving different stakeholders in policy making while avoiding potential conflicts. The proposed methodology was validated by showing the possibility of its application on a real example and obtaining a compromise solution accepted by all involved stakeholders. The robustness of the multicriteria analysis allows any changes to be implemented and evaluated, according to particular stakeholders' requirements and preferences. Furthermore, due to different changing conditions in the future, the importance of some criteria could be modified as well. For instance, fuel price, which is marked as the most important criterion by the shipowners and the government, might change due to different conditions (market conditions, competitors, or legal framework), and this methodology allows such changes to be easily implemented in the decision-support framework.

It is of genuine importance to emphasize that switching to alternative fuels (except LNG) would have impact on the rapid rise in demand; i.e., a massive investment in production capacity will be required. Theoretically, since the current LNG production is higher than the shipping industry's energy requirement and the share of LNG in the total gas market is only 10%, a switchover of the entire global fleet to LNG would be possible. Additionally, the energy need of the global fleet could be covered by LPG; but, in this case, no LPG would be left for other industrial sectors and users [44]. In this context, from the government point of view, the interactions of different fuels with other industrial sectors should be taken into consideration.

Further, each Member State is obliged to adopt National Policy Frameworks (NPF) for the development of the market as regards alternative fuels in the transport sector and the deployment of the relevant infrastructure pursuant to Article 10 (2) of Directive 2014/94/EU. According to adopted NPF, Croatia will emphasize the simultaneous development of infrastructure and markets for all alternative fuels in transport. Compared to other alternative fuels, the filling infrastructure for hydrogen is the least developed. Furthermore, regarding shore-side electricity supply points (ESP) there are currently two inland waterways ports that offer ESP, and the 2025 target is to have seven shore-side electricity supply points in TEN-T Core Network ports. Regarding LNG, there are no LNG refueling points in the maritime ports in Croatia. The NPF target is one LNG refueling point in the TEN-T Core Network by 2025 (port of Rijeka) and in total seven maritime LNG refueling points (located in the main ports) in 2030. In the scenario developed for the purposes of NPF, by 2040, LNG ships that are engaged in coastal liner shipping will take up to 50% of the total energy consumption in the coastal shipping market [45]. Results obtained by this research follow the targets plotted in the NPF where the focus is placed precisely on upgrading/building the seven shore-side electricity supply points and LNG refueling points. In the final ranking of the alternatives, hydrogen also gained relatively high scores from all three groups of stakeholders, but for example this fuel is not considered for transport in NPF. In this context, where the national goals and planned actions are set, when reaching final decisions, a compromise between the different groups of stakeholders may be needed; indeed, this would be crucial. The government experts will certainly look at the wider context in order to adhere to the drawn development guidelines.

This analysis, likely the first of this type in this area, can serve as a solid basis for strategic planning. In drafting a new Strategy of Maritime Development and Integrated Maritime Policy in Croatia, a set of policies considering alternative marine fuels can be developed applying an approach similar to the one presented in this paper. This approach could be applied to policy making in other areas by adapting the respective alternatives, goals, and criteria. The findings of this study have to be seen in light of some limitations. One of the limitations of this study could be related to the different types of ships used in coastal transportation (fast ships, ro-ro), so further research can analyze alternative fuel options for each particular type of ship. Future research could be based on a wider range of experts as well as a combination of available data from other similar studies. Furthermore, selection of an alternative fuel should be evaluated considering the energy–quantity ratio, which reflects on the space requirements for fuel storage and additional operational costs.

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