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ASSESSING KEY FACTORS IN MARINE MAIN ENGINE SELECTION USING FUZZY AHP METHOD

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ABSTRACT

The main engine selection is a critical decision in the shipbuilding process, as it impacts the vessel's overall performance, efficiency, and operational costs. In this article, we present a comprehensive evaluation of marine engine selection criteria using Fuzzy Analytical Hierarchy Process (AHP). This approach provides a systematic framework for evaluating the criteria based on their relative importance, incorporating both qualitative and quantitative data. In the selection of the main engine, three main criteria were determined as economic criteria, technical criteria, and company-related criteria, and each main criterion was detailed with four sub-criteria. The results indicated that after considering the relative significance of each sub-criterion, fuel oil consumption emerged as the top priority, accounting for 17.01% of the overall importance. Following closely behind, easy operation held the second position with a rating of 16.11%, signifying its considerable importance.

Keywords: *Main Engine Selection, Merchant Ships, Shipbuilding, Decision-Making, Fuzzy AHP*

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Gemi Ana Makine Seçiminde Temel Faktörlerin Bulanık AHP Yöntemi ile Değerlendirilmesi

ÖZET

Gemi ana makine seçimi, geminin genel performansını, verimini ve işletme maliyetlerini etkilediği için gemi inşa sürecinde kritik bir karardır. Bu çalışmada Bulanık Analitik Hiyerarşi Sürecini (AHP) kullanarak gemi ana makine seçim kriterlerinin kapsamlı bir değerlendirmesi yapılmıştır. Bu yaklaşım, nitel ve nicel verileri içeren kriterleri göreceli önemlerine dayalı olarak değerlendirmek için sistemli bir çerçeve sunmaktadır. Ana makine seçiminde, ekonomik, teknik ve şirketle ilgili kriterler olmak üzere üç ana kriter belirlenmiş ve her bir ana kriter dört alt kriter ile detaylandırılmıştır. Sonuçlar, her bir alt kriterin göreceli önemini birlikte değerlendirildiğinde, yakıt tüketiminin genel önemin %17.01'ini oluşturan en yüksek öncelik olarak ortaya çıktığını göstermiştir. Bunu yakından takip eden makinenin kolay kullanımı ise %16,11'lik oranla ikinci sırayı alarak büyük önem arz etmiştir.

Anahtar Kelime: *Ana Makine Seçimi, Ticari Gemiler, Gemi İnşa, Karar Verme, Bulanık AHP*

1. INTRODUCTION

Making decisions is an important factor that will play a significant role in determining the outcome of any given event. It entails examining choices, reflecting on their potential outcomes, and selecting the most suitable option. Successful decision-making requires an in-depth understanding of the situation, well-defined objectives, and the ability to evaluate and compare numerous options. Fuzzy decision-making utilized when the information available for solving a problem is unclear and insufficient, is a commonly studied subject in academic literature. The Fuzzy Analytical Hierarchy Process (AHP) method is one of the widely used fuzzy decision-making techniques and has seen successful implementations in many fields (Cebi et al., 2016; Kahraman et al., 2015; Kaya et al., 2019; Mardani et al., 2015).

Further, fuzzy AHP is a popular tool in several maritime areas, including naval architecture, maritime transportation, maritime risk management, marine engineering, etc. It makes the incorporation of subjective knowledge and ambiguity possible, which ultimately leads to findings that are more accurate and reliable. Fuzzy AHP offers a flexible and organized framework for decision making in the maritime sector by considering a wide range of factors and expert opinion. This method provides valuable insights and enables more informed decision making in a wide range of maritime applications. For instance Kafalı and Özkök

(2015) used fuzzy AHP to assess the criteria for shipyard selection by shipowners. Türk and Özkök (2020) utilized the Fuzzy AHP method to assess the critical factors in choosing a shipyard location. The same research group (2022) also evaluated the risk of falling accidents in shipyards. Şahin and Yip (2017) effectively applied the Fuzzy AHP approach in the selection of technology in the maritime industry. Çelik and Akyüz (2018) performed a Fuzzy AHP study in the maritime transportation sector. Şahin and Şenol (2015) conducted an analysis of marine accidents using the Fuzzy AHP method. Kassav et al. (2022) carried out a Fuzzy AHP implementation in the field of maritime supply chains.

As was briefly discussed earlier, numerous decision-making issues can be found in a variety of maritime areas, and associated research is carried out in an effort to find answers to these issues. One of the significant decision-making problems in maritime sector is the selection of the main engine for a ship. Selecting the main engine is a crucial step in the shipbuilding process. When it comes to selecting the main engine for a ship, there are a few key considerations to keep in mind. It is necessary to appropriately determine these criteria and to establish the degree to which each of them should be given importance. When this is completed, selecting the best option from the alternatives is simple. The main engine of the ship not only meets the energy needs of the ship, but also affects safety, efficiency, cost, and environmental factors. In light of this, ship owners can obtain long-term economic and operative benefits from making the most effective decision.

Although the selection of ship's main engine is of vital importance, there is surprisingly little research in the academic literature on the topic of ship main engines. In a study by Bulut et al. (2015), they used the AHP method to choose a main engine for a Panamax bulk carrier. The main motivation of the study was to compare the fuzzy AHP using the rotational priority search (RPI) method and the classical fuzzy AHP method. In the study, six key criteria were identified, power, cost of purchase, fuel consumption, maintenance, majority in the current merchant fleet, damage history of the main engine model. For the case study, six alternative models were selected from two major manufacturers, with power capacities ranging from 8,000 to 14,000 kW. According to the classic fuzzy AHP analysis, cost of purchase and popular usage in the current world fleet were the most important criteria, followed by power, fuel consumption, damage history and maintenance, respectively. Then, RPI method was performed and it was determined that the results were largely similar to the classic fuzzy AHP. While there were some differences in the importance levels of the last three criteria, the first two criteria were obtained as similar.

In the study conducted by Herişçakar (1999), AHP and SMART methods were used in ship main engine selection. The case study focused on a 6000 DWT chemical tanker, whose main engine power was 4000 kW. The study identified five key objectives when it came to choosing the main engine: low cost, reliability, best technical features, easy maintenance and handling, and compliance with international rules and regulations for the environment. Later, these main objectives were turned into first-level criteria such as financial criteria, reliability, technical features, maintenance and environment, and related sub-criteria were added to them. Six options with a total power of about 4000 kW were selected. At the end of the study, SULZER 6ZAL40S and DEUTZ 645L8 were the best alternatives with the SMART method, while SULZER 6ZAL40S was the alternative with the best score in the solution with AHP.

Uzun and Kazan (2016) compared three methods, AHP, TOPSIS and PROMETHEE, for selection a marine engine. They applied the methods to a fishing vessel, the NB 25 Wartsila. The study considered 12 criteria and evaluated 7 main engines to determine the most suitable engine for the vessel. The main criteria were; technical specifications, contract criteria, reliability, operating costs and maintenance costs. The technical features were further divided into sub-criteria such as power, speed, weight, volume, class requirements and other technical competencies. The contract criteria included initial investment cost and delivery time, while the operating costs were further divided into fuel consumption and oil consumption. As a result of the application, it was observed that the AHP and PROMETHEE methods produced similar results. In general, Wartsila, MAN, and MAK were determined as the best alternative.

Previous studies have not thoroughly explored the problem of ship main engine selection and mainly focused on comparing different methods. They also lacked examination of the details of the ship main engine selection problem, leading to weaknesses in criteria determination. For instance, engine power is often used as a criterion, but it is determined at the design stage and should only be considered as a constraint. In other words, before starting a ship's main engine selection, the ship's engine power must be determined and the selection is carried out among the engines with a power close to this value.

The main purpose of the presented study was to evaluate the marine main engine selection criteria. First, the ship main engine selection problem was explained in detail. Then, the main engine selection criteria for a merchant ship were determined by considering the literature and expert opinions. Finally, a pairwise comparison of the criteria was performed and the importance weights were calculated with the fuzzy AHP method. Because one of the most important steps in the selection of the main engine is the selection of the appropriate one among the alternatives, this study revealed the necessary criteria for selection stage. It is thought that the present study will serve as a valuable resource for researchers working in the field of selection of marine main engine. The main contributions of this study can be summarized as follows: (i) the ship main engine selection problem is presented in a comprehensive way, (ii) the main engine selection criteria for a merchant ship are determined, (iii) the importance weights of the main engine selection criteria are calculated.

2. MARINE ENGINE SELECTION PROBLEM

Determining the ship's main engine is an iterative process consisting of calculating the ship's main engine power and selecting the appropriate main engine. In general, the ship main engine determination process can be summarized in seven steps as shown in Figure 1 (Diesel, 2018).

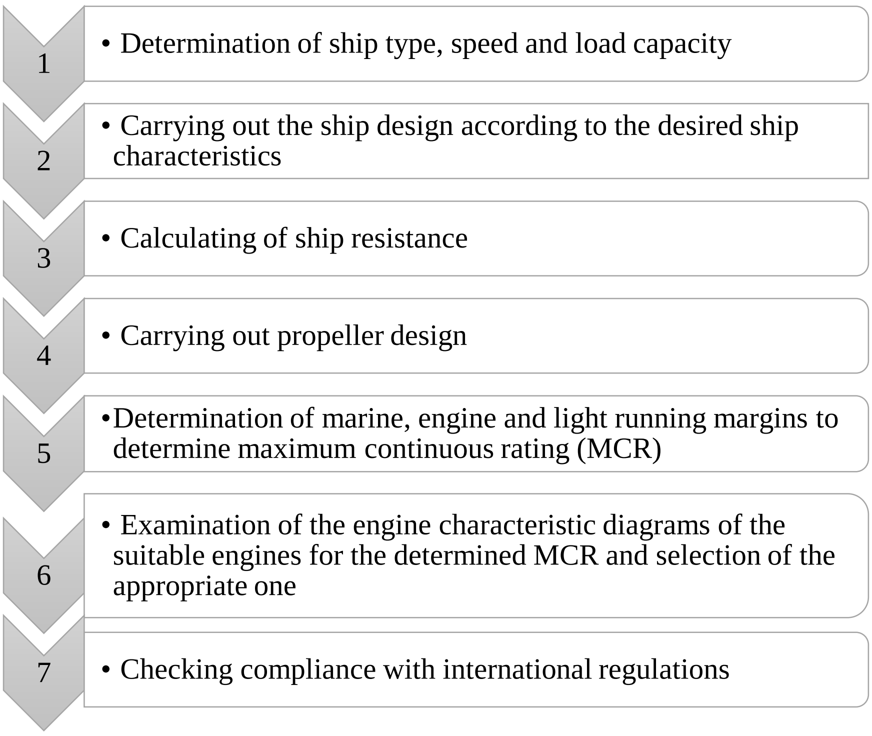

Figure 1: Main engine selection spiral (Diesel, 2018).

First of all, the desired load capacity and service speed of the ship are determined by the ship owner. Then, the ship design is carried out according to the desired ship characteristics. In the third step, ship resistance calculations are carried out. Then, propeller design is performed. In the initial project phase, the required propeller power and propeller rpm estimates are based on theoretical calculations of calm water resistance for loaded ship and propeller working conditions behind the hull. After the resistance calculations are validated, the design is further optimized by experimental towing tank tests to obtain the final propeller curve for the project. In the step 5, some margin must be added to the propeller design point (PD). One of these, the sea margin, includes resistance increase caused by the expected average wind and waves. A reasonable sea margin ranging from about 10% to 30% depending on the project must be established by the designer. Another margin added to the propeller design point is the engine margin. Generally, it is not desirable to use 100% engine power for normal operation due to increased fuel consumption and a desire for power reserve. For this reason, an engine margin is often added. Engine margin can vary between 10% and 30% depending on the priorities of the project. In addition, the engine margin can be higher than conventional engine margins to comply with the "IMO Minimum Propulsion Requirements" regulation. Weather conditions change during the voyage of the ships, and over time, contamination occurs on the hull and propeller. During the voyage of the ships, contamination occurs on the hull and propeller. As it is known, a dirty hull reduces the speed of the arriving water and increases the slip on the propeller. In addition, ship resistances increase in cruising in heavy seas. Therefore, the light running margin is also added. After adding all the margins, the SMCR point is obtained and the appropriate main engine for this point is determined (Diesel, 2018; Gürgen, 2021).

At this stage, there are many criteria depending on the project and the selection is made by evaluating these criteria. In general, the selection of the engine with greater power causes a decrease in fuel consumption, while increasing the initial investment cost and machine dimensions. Therefore, it is inevitable to use decision-making methods to evaluate these criteria. The last stage of the ship main engine selection process is to check the compliance of the selected engine with international regulations. NO_X and SO_X emission restrictions and regulation of EEDI are the leading ones. EEDI was introduced by IMO to reduce greenhouse gases from ships. If the EEDI is high, options such as speed reduction, hull optimization and specific fuel consumption reduction should be considered by returning to the first step and this process should be repeated until the restrictions are met. (Diesel, 2018; Gürgen, 2021).

As mentioned above, determining the most suitable one among the main engine options is a decision-making problem involving many criteria. Therefore, at this stage, the main engine selection criteria must be determined appropriately and they must be weighted. In this study, the criteria for selecting the main engine of a merchant ship were established through review of existing literature and consultation with marine engineers, as presented in Figure 2.

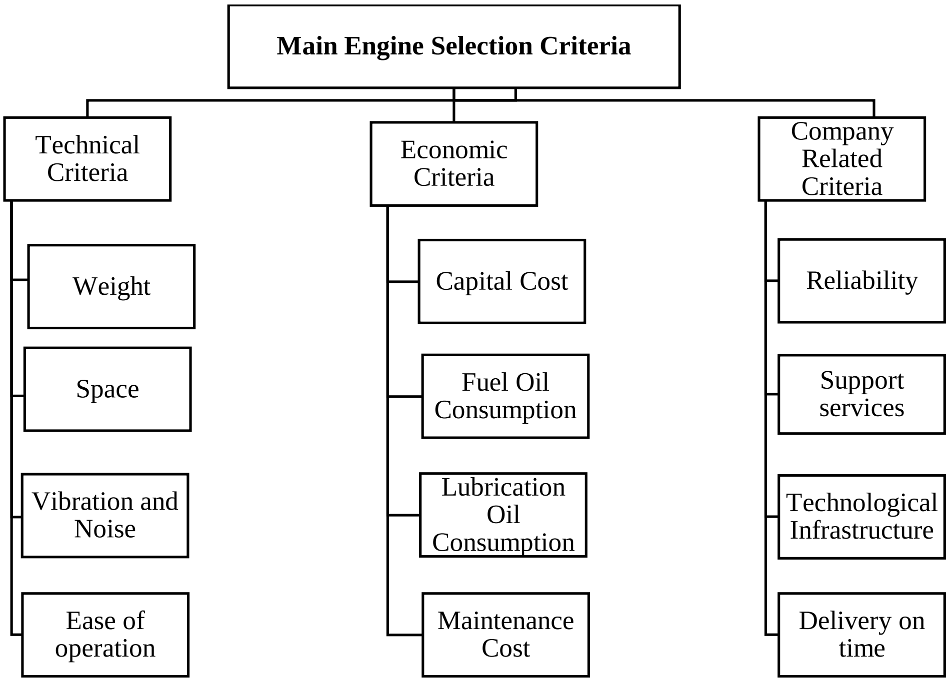

Figure 2: Main engine selection criteria for a merchant ship

As shown in Figure 2, there are 3 main criteria and 12 sub-criteria in main engine selection. The sub-criteria of technical criteria were determined as main engine weight, space, vibration-noise and easy operation. Engine weight is usually not a very important issue for the majority of merchant ships. However, it plays a very important role in ferries and high-speed boats. The power-to-weight ratio is vital in the design of warships and catamarans, as high speed is required from a relatively small ship. Engine dimension is considered as an important criterion in the selection of a main engine. Reducing the dimension of the engine will cause the engine room to be smaller and increase the cargo carrying capacity of the ship. However, height can also be a constraint, especially for low-speed two-stroke engine. In addition, since the volume is a priority issue in warships, the power/volume ratio is very important for these ships. Vibration and noise are factors that can cause problems in both the engine room and the living space. Today, there are international standards that must be complied with for both noise and vibration. In addition, it is desired that the vibration and noise level be as low as possible. Noise and vibration are becoming more important for some vessels, such as cruise ships, fishing vessels, oceanographic vessels, and warships operating submarine detection equipment. The marine engineers want to work on diesel engine that are light and easy to maintain, with less maintenance parts. In addition, new technologies such as hybrid and dual fuel are not preferred by conservative marine engineers due to system complexity and lack of experience. If a ship's main engine is not fully understood by the marine engineer, a negative aspect of that machine will be formed due to usage errors (Gürgen, 2021; Herişçakar, 1999; Watson, 1998).

The sub-criteria of economic criteria were determined as initial investment cost, fuel consumption, oil consumption and maintenance cost. The purchasing cost of the ship's main engine is undoubtedly one of the important criteria for choosing an engine. The cost of the main engine also includes the transportation cost and the installation (gear box, pump, etc.) cost. Fuel consumption of a marine main engine has a significant share in operating costs. The preference of engine with lower fuel consumption contributes to the reduction of operating costs. In order to make comparisons between the machines in terms of fuel consumption, the specific fuel consumption is usually given in the catalogs instead of the fuel consumption. Specific fuel consumption shows the amount of fuel consumed by an engine per kilowatt hour, and its unit is expressed in g/kWh. The decrease in the specific fuel consumption of an engine depends on its efficiency. As it is known, lubrication is used in ship engine to reduce friction. The fuel injected into the cylinder mixes with the oil film between the piston ring and the cylinder liner, and some oil burns together with the fuel. However, there are some factors that affect oil consumption. Examples of these are engine design, operating conditions, oil and fuel quality, system losses and maintenance status. The cost of cylinder lubricating oil is one of the biggest contributors to total operating costs, alongside the cost of fuel. The maintenance cost of a ship's main engine is one of the important factors affecting the sustainability of the machine. The number and cost of maintenance parts are factors that directly affect the maintenance cost. For example, an increase in the number of cylinders for a main engine will cause an increase in the number of parts requiring maintenance. In addition, the cost of spare parts is also considered as an important parameter and varies according to the manufacturers (Diesel, 2018; Gürgen, 2021; Herişçakar, 1999; Watson, 1998).

The sub-criteria of the company (engine manufacturer) related criteria were determined as reliability, support services, technological infrastructure and delivery on time. While reliability is important for all ships, it is especially very important on ocean-going ships. Also, reliability is vitally important for warships, and the main engine must be highly reliable to minimize the consequences of any loss of capability from mechanical failure or enemy movement. Generally, main engine that have been tried before and proven to be reliable by marine engineers are preferred. Main engines with frequent breakdowns and complex systems are not preferred. Support services include customer service, technical support, repair-maintenance services and training support. In particular, the supply of spare parts should be easy and accessible. Any problem in the supply of spare parts can cause very heavy economic losses for the ship. The technological infrastructure of the engine manufacturer is very important in terms of their competition with each other. The existence of environmentally friendly technologies that reduce fuel consumption and exhaust emissions, waste heat recovery systems and technologies, and R&D activities are evaluated within the technological infrastructure. Especially in order to meet the international restrictions introduced in recent years, the above-mentioned parameters are of great importance. Delivery on time and assembly of the main engine in the shipbuilding process is one of the important criteria. Failure to deliver the main engine at the time specified in the project delays the launch of the ship and causes serious economic losses for both the shipyard and the ship owner. In addition, shipyards do not want the main engine to be delivered early in order to reduce storage costs. Therefore, delivery on time of the engine is considered as an important criterion (Gürgen, 2021; Herişçakar, 1999; Watson, 1998).

3. FUZZY AHP METHOD

For real-world problems, decisions are accomplished using incomplete and non-numerical information. The decision makers generally prefer to make judgments within certain intervals due to the fuzzy nature of the process of comparing alternatives, rather than making fixed-valued judgments. The classical AHP method created by Satty (1980) has a major drawback because it utilizes precise expressions. For this reason, researchers have combined the fuzzy theory presented by Zadeh (1965) with the classical AHP method to present more realistic tools for real-world decision making problems. In 1983, triangular fuzzy numbers were used for the first time in the AHP method with the study by Laarhoven and

Pedrycz (1983). In the following years, this idea was adopted and different approaches were presented by many researchers. The most well-known of these are the studies by Buckley (1985) and Chang (1996). The extended fuzzy AHP method presented by Chang was used in the study, and the steps of the method are given below.

In Chang (1996)'s fuzzy extend analysis method, $X = \{x_1, x_2, \ldots., x_n\}$ is a set of objects and $U = \{u_1, u_2, \ldots., u_n\}$ is goal set. Thus, m extend analysis values for each object can be given as follows:

$$M^1{}_{g_i}, M^2{}_{g_i}, \ldots M^m{}_{g_i}, i = 1,2, \ldots, n \tag{1}$$

where $M^j{}_{g_i}$ $(j = 1,2, \ldots, m)$ are triangular fuzzy numbers.

Step 1: The fuzzy synthetic extent for the i-th object is computed using the following formula.

$$S_i = \sum_{j=1}^{m} M_{g_i}^j \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^j\right]^{-1} \tag{2}$$

$\sum_{j=1}^{m} M_{g_i}^j$ is calculated as the following equation.

$$\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j\right) \tag{3}$$

$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^j\right]$ expression at the Equation 2 can be determined as follows:

$$\sum_{\mathrm{i}=1}^{\mathrm{n}}\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right) \tag{4}$$

Then, the inverse of the vector is calculated as follows

$$\left[\sum_{\mathrm{i}=1}^{\mathrm{n}}\sum_{j=1}^{m} M_{g_i}^j\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \tag{5}$$

Step 2: The degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is given as:

$$V(M_2 \geq M_1) = \sup_{y \geq x}\left[\min\left(\mu_{M1}(x), \mu_{M2}(y)\right)\right] \tag{6}$$

$M_1 = (l_1, m_1, u_1)$ and $M_2 = (l_2, m_2, u_2)$ are triangular fuzzy numbers and the degree of possibility is calculated as follows:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) = \begin{cases} 1 \quad , & m_2 \geq m_1 \\ 0 \quad , & l_2 \geq u_1 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} , & otherwise \end{cases} \tag{7}$$

where *d is* y-axis value of the highest intersection point D between μ_{M_1} and μ_{M_2}, and is shown in Figure 3.

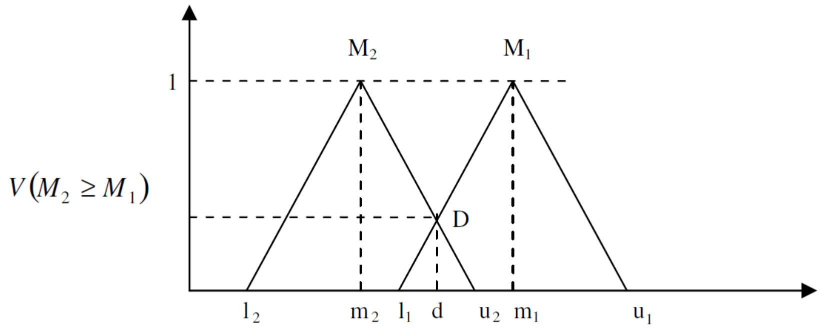

Figure 3: The intersection of M_1 and M_2 fuzzy number

Step 3. The degree of possibility for a fuzzy number to be greater than k fuzzy numbers can be defined as follows:

$$V(M \geq M_1, M_2, \ldots, M_k) = V[(M \geq M_1) \text{ ve } (M \geq M_2) \text{ ve} \ldots (M \geq M_k)] = \min V(M \geq M_i), \text{ i} = 1, 2, 3, \ldots, \text{k} \tag{8}$$

for k= 1, 2, …, n ; $k \neq I$, assume that $d'(A_i) = \min V(S_i \geq S_k)$, then the weight vector is given as follows:

$$W' = (d'(A_1), d'(A_2), \dots, d'(A_n))^T \tag{9}$$

Step 4. Finally, W' is normalized and W is produced as follows:

$$W = (d(A_1), d(A_2), \dots, d(A_n))^T \tag{10}$$

Generally, evaluations are performed by more than one expert or decision maker for fuzzy AHP applications. Then, the above-mentioned steps are carried out by aggregating obtained evaluations and aggregated results need to be consistent. However, although consistency analysis is a critical step for group decision making, it is often overlooked in the literature. In this study, central consistency index (CCI) proposed Bulut et al. (2012) based on the geometric consistency index (Aguarón and Moreno-Jiménez, 2003; Crawford and Williams, 1985) was used. $A = (a_{Lij}, a_{Mij}, a_{Uij})$ is fuzzy decision matrix and $w = [(w_{L1}, w_{M1}, w_{U1}), (w_{L2}, w_{M2}, w_{U2}), \dots, (w_{Ln}, w_{Mn}, w_{Un})]^T$ is priority vector derived from A vector. The CCI is calculated as follows:

$$CCI(A) = \frac{2}{(n-1)(n-2)} \sum_{i<j} (\log\left(\frac{a_{Lij} + a_{Mij} + a_{Uij}}{3}\right) - \log\left(\frac{w_{Li} + w_{Mi} + w_{Ui}}{3}\right) + \log(\frac{w_{Lj} + w_{Mj} + w_{Uj}}{3}))^2 \tag{11}$$

A value of $CCI(A)$ equal to zero indicates that the matrix is completely consistent. In the study by Aguarón et al. (2003), $\overline{GCI}$ values according to the number of criteria are given as follows:

- $\overline{GCI} = 0.31 \quad (n = 3)$
- $\overline{GCI} = 0.35 \quad (n = 4)$
- $\overline{GCI} = 0.37 \quad (n > 4)$

where n is number of criteria. CCI is fuzzy version of $\overline{GCI}$ and the matrix will be consistent when $CCI(A) < \overline{GCI}$

4. IMPLEMENTATION

In general, the criteria to be considered during the selection process of the main engine selection of a ship have been explained in Section 2 and illustrated in Figure 2. Furthermore, specific criteria to a particular project can also be considered by incorporating them into the selection process. In this study, the evaluation of the effective criteria in the selection of the main engine of a ship was carried out using the Fuzzy Analytical Hierarchy Process (AHP) method proposed by Chang (1996). The steps taken towards this objective are shown in Figure 4.

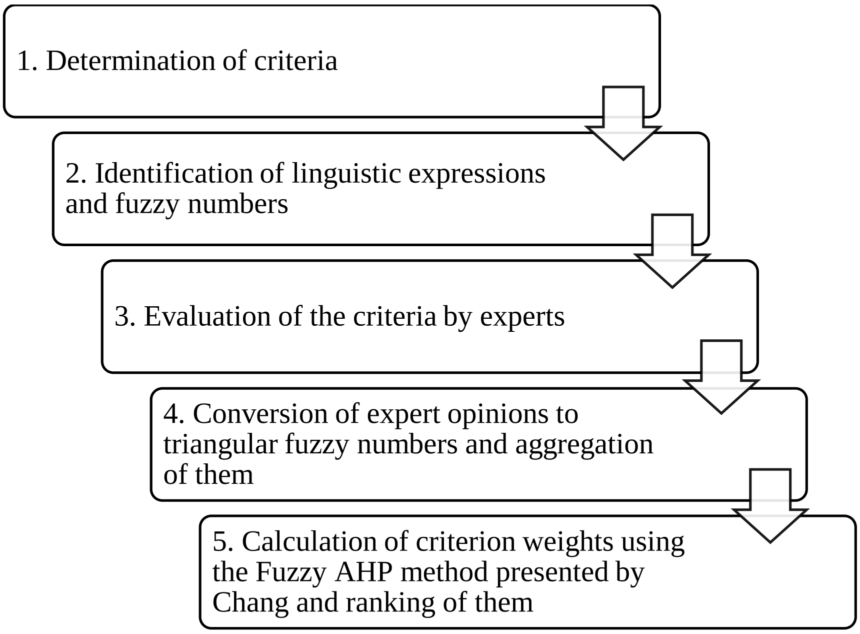

Figure 4: The main steps in the evaluation of ship main engine selection criteria

As seen in Figure 4, the first step of identifying the criteria has been discussed in the second section. Then, the linguistic expressions are defined as in Türk and Özkök's study (2020). Linguistic expressions and fuzzy sets are given in Table 1.

Table 1: Linguistic expressions and fuzzy sets

Linguistic expressions	**Fuzzy sets**
Equally important (E)	(1, 1, 1)
Moderately more important (M)	(1, 3, 5)
Strongly more important (S)	(3, 5, 7)
Very strongly more important (VS)	(5, 7, 9)
Demonstratively more important (D)	(7, 9, 9)

After the criteria and linguistic expressions were determined, expert opinions were collected. Questionnaires containing pairwise comparisons of the main and sub-criteria were prepared and the verbal answers given by the engineers specialized in the field of ship engine were recorded. Evaluations were carried out by considering a merchant ship such as a container ship, tanker, general cargo ship. A total of 5 experts participated in the study and the impact weights of the experts were taken equally. All the answers obtained were converted into triangular fuzzy numbers in order to apply the method, and the answers given by each expert to the related question were collected and aggregated decision matrices were formed. Finally, the consistency of the decision matrices was checked and the method was applied. Please take note that this study provides a general assessment for selecting conventional diesel main engines in commercial ships. Within a broad framework, these findings can be deemed reasonable for studies conducted in the sub-classes of commercial ships. However, it is important to acknowledge that conducting separate studies with different experts for each sub-class may result in slight variations in the weighting of criteria. Furthermore, it is worth noting that significantly different outcomes can arise for ships with diverse concepts, such as warships.

5. RESULTS AND DISCUSSION

Since there are five experts in the study, it is necessary to obtain aggregated decision matrices. The arithmetic average method was applied by taking the effect values of all experts equal in the aggregation stage. As a result, the aggregated matrix for the main criteria, technical criteria, economic criteria and company-related criteria were given in Table 2, 3, 4 and 5, respectively.

Table 2: Aggregated pairwise comparisons for the main criteria

	Technical criteria	Economic criteria	Company-related criteria
Technical criteria	(1, 1, 1)	(0.49, 0.93, 1.50)	(2.28, 3.53, 5)
Economic criteria	(2.04, 3.27, 4.61)	(1, 1, 1)	(2.04, 3.66, 5.4)
Company-related criteria	(0.47, 1.31, 2.17)	(0.33, 0.80, 1.50)	(1, 1, 1)

Table 3: Aggregated pairwise comparisons for the technical criteria

	Weight	Space	Vibration and Noise	Ease of operation
Weight	(1, 1, 1)	(0.31, 0.36, 0.54)	(0.89, 1.72, 2.69)	(0.15, 0.22, 0.54)
Space	(3.00, 4.61, 6.21)	(1, 1, 1)	(1.06, 1.48, 2.02)	(0.47, 0.50, 0.57)
Vibration and Noise	(2.27, 3.53, 4.49)	(2.03, 2.84, 3.26)	(1, 1, 1)	(0.71, 1.17, 1.77)
Ease of operation	(3.00, 5.02, 7.01)	(2.60, 3.80, 5.01)	(2.42, 4.04, 5.68)	(1, 1, 1)

Table 4: Aggregated pairwise comparisons for the economic criteria

	Capital Cost	Fuel Oil Consumption	Lubrication Oil Consumption	Maintenance Cost
Capital Cost	(1, 1, 1)	(0.87, 1.69, 2.54)	(1.85, 2.68, 3.53)	(0.82, 1.64, 2.46)
Fuel Oil Consumption	(2.66, 3.92, 5.29)	(1, 1, 1)	(2.60, .4.60, 6.60)	(1.62, 2.42, 3.24)
Lubrication Oil Consumption	(1.45, 2.26, 3.12)	(0.15, 0.24, 0.57)	(1, 1, 1)	(0.88, 1.31, 1.86)
Maintenance Cost	(1.08, 1.53, 2.20)	(1.46, 1.90, 2.44)	(2.83, 4.06, 4.88)	(1, 1, 1)

Table 5: Aggregated pairwise comparisons for the company-related criteria

	Reliability	Support services	Technological Infrastructure	Delivery on time
Reliability	(1, 1, 1)	(1.67, 2.50, 3.37)	(2.26, 3.49, 4.84)	(2.02, 2.84, 3.66)
Support services	(2.51, 3.47, 4.72)	(1, 1, 1)	(1.80, 2.60, 3.40)	(2.20, 4.20, 6.20)
Technological Infrastructure	(1.27, 2.12, 2.97)	(0.65, 0.68, 0.73)	(1, 1, 1)	(1.88, 3.13, 4.60)
Delivery on time	(1.05, 1.46, 1.91)	(0.17, 0.26, 0.70)	(0.49, 1.34, 2.30)	(1, 1, 1)

After the aggregated decision matrices were obtained, consistency analysis was performed. The central consistency index proposed by Bulut et al. (2012) was used for the consistency analysis. The consistency ratios of the aggregated decision matrices for the main and sub-criteria, and the maximum values according to the number of relevant criteria were given in Table 6. The results indicated that the consistency ratio of all decision matrices was lower than the maximum value, leading to the conclusion that all decision matrices were deemed consistent.

Table 6: The consistency ratio of aggregated decision matrices

Main and sub criteria	Maximum value	Consistency ratio
Main criteria	$CCI_{max} = 0.31$	0.2077
Technical criteria	$CCI_{max} = 0.35$	0.2255
Economic criteria	$CCI_{max} = 0.35$	0.2030
Company-related criteria	$CCI_{max} = 0.35$	0.1599

After showing that the combined decision matrices are consistent, the important weights of all main and sub-criteria were calculated with the fuzzy AHP method proposed by Chang (1996). The crisp and normalized weights of all main and sub-criteria were given in Table 7. In addition, the relative weights of the sub-criteria were calculated by taking into account the weight of the relevant main criteria.

Table 7: The important weights of main and sub criteria

Main and sub criteria	Normalized crisp weights	Relative crisp weights
Technical Criteria	**0.348**	-
Weight	0.004	0.001
Space	0.250	0.087
Vibration and Noise	0.283	0.098
Ease of operation	0.463	0.161
Economic Criteria	**0.456**	-
Capital Cost	0.23	0.105
Fuel Oil Consumption	0.373	0.170
Lubrication Oil Consumption	0.124	0.057
Maintenance Cost	0.273	0.124
Company Related Criteria	**0.196**	-
Reliability	0.314	0.062
Support services	0.347	0.068
Technological Infrastructure	0.228	0.045
Delivery on time	0.111	0.022

The findings indicated that economic criteria were the most crucial of the main criteria, followed by technical criteria and company related criteria respectively. These results revealed that economic criteria were the most influential factor in selecting a main machine, with a 45% impact. Despite being the least effective criteria, the significance of company related criteria cannot be ignored.

Figure 5 presents the technical criteria's importance weights as percentages. The most critical criteria was found to be ease of operation, with a 46% weight. This was followed by vibration and noise, volume, and weight, respectively. It's not surprising that weight was considered the least important in the selection of a main engine for a merchant ship.

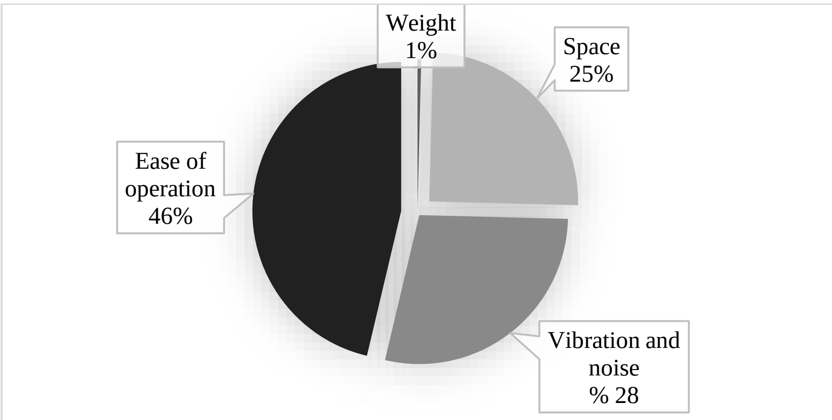

Figure 5: The importance weights of the technical criteria

In Figure 6, the importance weights of the economic criteria were shown as percentages. The criterion with the highest importance was determined as fuel consumption. Then, the maintenance cost and the capital cost were important criteria, respectively. Lubrication oil consumption was the least effective criterion with a weight of 13%.

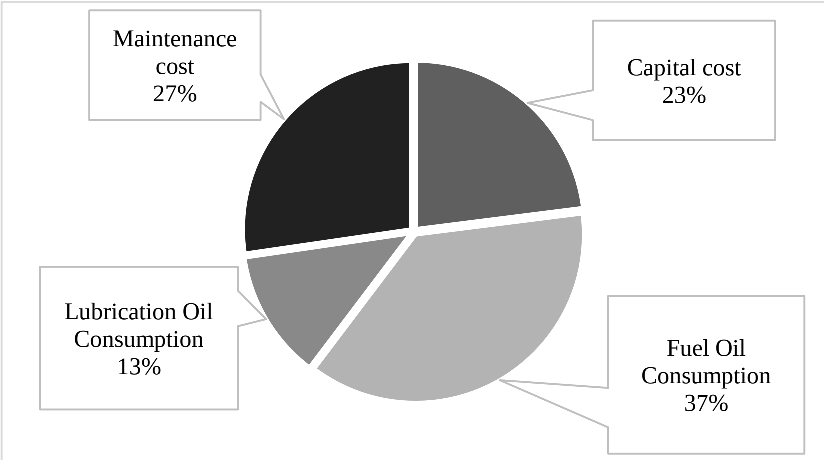

Figure 6: The importance weights of the economic criteria

The importance weights of the company related criteria were shown in Figure 7 as a percentage. Among the sub-criteria related to the company, the most important criteria was determined as support services with a value of 35%. This was followed by reliability, technological infrastructure and delivery on time, respectively.

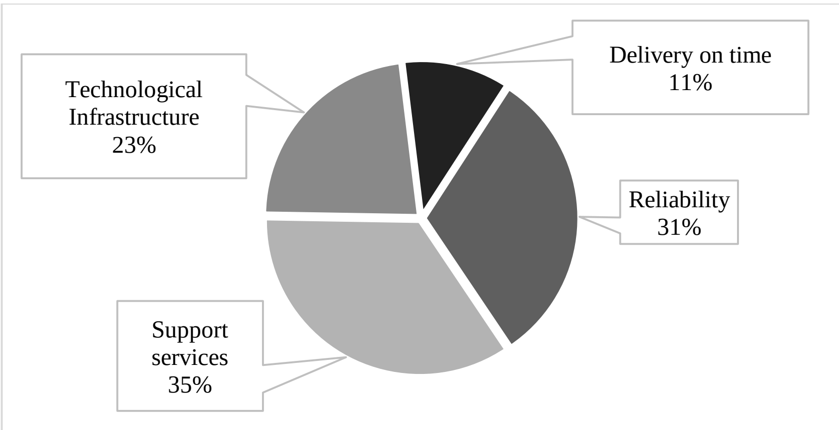

Figure 7: The importance weights of the company related criteria

Comparison of all sub-criteria was shown in Figure 8. The most important criterion among the sub-criteria is fuel oil consumption with a value of 17.01%. The fuel consumption of the main engine, which has a large share in the ship operating costs, is desired at the lowest possible level. Therefore, it is reasonable to determine fuel consumption as the most important criterion. Especially considering the long-term, the selection of the main engine with lower fuel consumption is of great importance. Easy operation of the main engine was the second most important criterion with a value of 16.11%. As it is known, the main engine of the ships is operated by the marine engineer, and they have two big expectations for the main engine: the main engine has few parts that require maintenance and its easy operation. Engine weight was the least effective criterion with a value of 0.14%. The fact that weight was not an important criterion for merchant ships was effective in this result. However, weight would be crucial if a main engine was chosen for a warship.

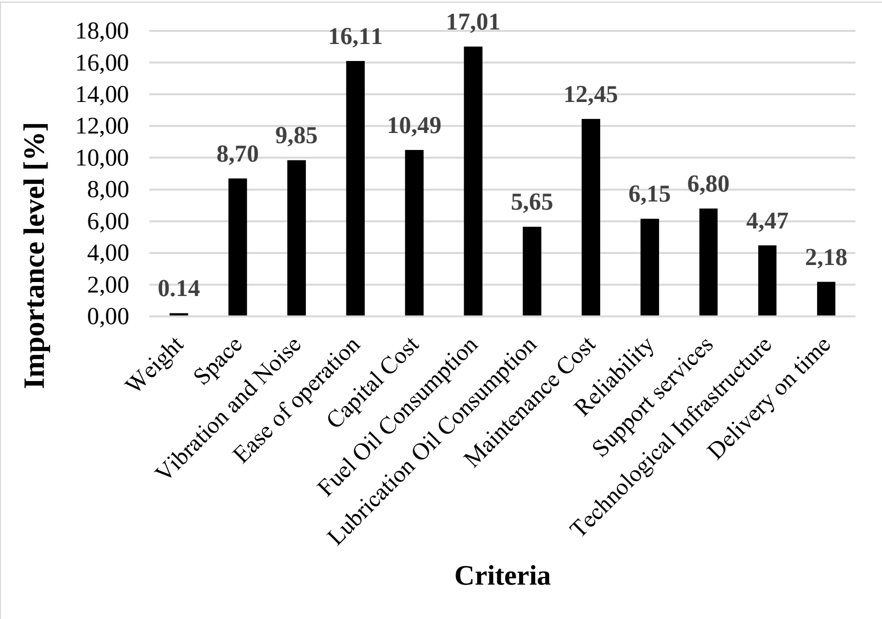

Figure 8: The relative weights of all sub-criteria

6. CONCLUSION

This study aimed to evaluate the key factors in the selection of a marine main engine using the Fuzzy AHP method. The study analyzed the main criteria such as economic criteria, technical criteria, and company-related criteria. The technical criteria were divided into sub-criteria of main engine weight, space, vibration-noise, and ease of operation. The economic criteria were split into initial investment cost, fuel consumption, oil consumption, and maintenance cost. The criteria related to the engine manufacturer were reliability, support services, technology infrastructure, and timely delivery.

As a consequence of the findings of the research, when the main criteria were compared with each other, it became clearly obvious that the economic factors were the most significant aspect. The economic criteria were the first to be considered, then the technical criteria, and finally the company-related factors. When the importance levels of each of the sub-criteria were taken into account, it was concluded that fuel oil consumption was the most important factor, scoring 17.01% importance. With a rating of 16.11%, easy operation took the position as the second most important factor. After these came the maintenance costs then the cost of capital, then the vibration and noise levels, in that order. It was determined that weight was the was the least effective criterion in the selection of the main engine

In this study, fuzzy AHP method was used to evaluate the main and sub-criteria. The use of the Fuzzy AHP method allows for a more comprehensive analysis of the criteria, taking into account the uncertainty involved. Additionally, Fuzzy AHP method provides a systematic and structured approach for decision making, ensuring fairness and consistency. Overall, the utilization of Fuzzy AHP in decision making improves the accuracy and reliability of the decision making process. The findings emphasize the significance of fuel consumption and ease of operation and also suggest that company-related criteria should not be overlooked. The findings of this study can serve as a valuable reference for those involved in the selection process of a marine main engine. By highlighting the importance of various criteria, the study can guide decision-makers towards making informed choices.

Some potential studies can be conducted in the future. In this study, the traditional diesel engine has been taken into consideration as the main engine. However, the selection criteria for main engines for ships utilizing innovative motor technologies such as dual-engine and methanol-fueled engines can be evaluated. Detailed studies can be conducted for specific types of merchant ships. Additionally, a study can be carried out for warships where different criteria will be emphasized.

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