Selection of Desalination System for Commercial Vessels by Implementing Improved Intuitionistic Fuzzy TOPSIS Method

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1. Introduction

Water is vital for life and also has the first priority for seafarers on vessels. The water used in showers, sinks, urinals, toilet bowls, laundry, cooking, and washing dishes on ships can only be produced by desalinating seawater or by taking some freshwater from the port into a vessel’s tank. The water subject to desalination processes is called freshwater. The method used is called desalination [1]. Although the most used desalination method is distillation, the methods such as reverse osmosis, flash, and electrodialysis can also be used rarely [2].

In terms of freshwater consumption, while the average daily water consumption per person is 200 liters on passenger ships, this figure is approximately 60 liters per crew per day on cargo vessels [3]. Freshwater obtained by desalination must comply with certain controls. According to the International Standards Organization (ISO) standards, the water obtained from the sea should be heated to at least 80°C and disinfected by the boiling method [4]. According to the International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) Annex IV, the high-density brine portion of the distilled brine cannot be discharged within 12 nautical miles from the shore without the presence of a wastewater treatment equipment or disinfection system on board [5].

Another desalination method, which can be an alternative to the freshwater generator (distillation) and like the
reverse osmosis method (membrane filtration), is the ballast water treatment system, which has recently begun to be used. The Ballast Water Treatment System Convention, which regulates this system, entered into force in 2017 with the votes of the member states in the convention organized by the International Maritime Organization (IMO) of the countries affiliated with the United Nations (UN) [6].

Due to the ship’s own stability, the discharged cargo causes the ship to tend to raise the G (center of gravity) point or vice versa in a loading situation. As a result of these events, the ship’s officers must take ballast water to the ship’s lower segments, which are called ballast tanks, in order to keep the ship floating and reduce the swing period by reducing the G point of the vessel. Lowering the G point of the vessel would cause to increase in metacentric height (GM) and result in positive stability of the vessel. So, preparing the vessel that way would help to vessel’s tendency to resist capsizing. It is widely known and acknowledged by UN countries and companies that these ballast water intake or discharge operations could also carry microorganisms. As a result of the understanding of the damage to the environment caused by the microbiological organisms transported by the transport of the ballast water to other regions, commercial vessels have been forced into a new process by international conventions [7]. According to the convention text, later than this convention is signed, ballast water taken onboard will be passed through various filters before being taken to the ship and discharged, and if necessary, the harmful microbiological organisms will be eliminated by methods such as UV and ozonation [8].

The ballast water treatment system is an actual branch of the reverse osmosis method, which filters salt, dirt, and microorganisms through the relevant filters inside and then aims to fill the ballast tanks with purified water using the UV light or ozonation methods that kills harmful organisms [9]. The discharged ballast water passes through the ballast water treatment system for the second time, ultimately ensuring that pure, microorganism-free, and clean water is pumped out to sea [10]. In this way, the harmful organisms are not to be transported between different seas. So the harmful organisms that will multiply rapidly in the area will not be carried through ballast tanks and will not aid to kill existing microorganisms in different local ecosystems. The reason for the use of this method is the existing freshwater distillation method consumes a lot of energy per cubic meter, there is no suitable boiler on the ship that can meet the ballast tanks that occupy a large amount of volume, and the polluted water must be filtered somehow in any case [11].

Another goal of this study is to determine whether the reverse osmosis method is viable to use in commercial vessels or not, which is not mentioned in the literature but is currently heavily used by North Africa, the Middle East, and South Asian countries to treat seawater. With this, finding an answer to a question “whether the ballast water treatment system can be used as an alternative to the freshwater generator during desalination of the seawater or not” will be questioned.

The paper continues as follows. Literature review is conducted in Section 2. Section 3 gives the proposed methodology. Then, the criteria and alternatives in line with the relevant expert opinions and literature review are defined in Section 4. The application is completed in Section 5. Finally, results, recommendations, and future studies are given in Section 6.

2. Literature Review

The aim of the study is to investigate whether the reverse osmosis method and ballast water treatment system can be an alternative to the seawater distillation method (known as the evaporator method), which is currently actively used on ships. There are many studies on the related desalination methods in the literature. For example, Gluekstern and Priel [12] have designed seawater reverse osmosis filtration (SWRO) plantations that could be established for Israel and found that the cost for each 150,000 m³ of desalinated freshwater production is 0.5 US dollars. They also have revealed the fact that the SWRO method can be cheaper than other systems. They also have revealed the fact that the SWRO method can be cheaper than other systems. Choi [13] has kept the salinity rate at 10 ppm in his experiment on a freshwater generator producing 30 metric tons of freshwater per day and 1.5 metric tons per hour. He has proved that the capacity of the produced freshwater per cubic meter is not related to the low-temperature difference between weather conditions or the high-temperature difference between weather conditions. In addition, he has determined that the received seawater temperature is related to its initial temperature. Song et al. [14] have explained the relationship between the pressure applied to the transmembrane filter of the water to be treated and the percentage of recovered water. As a result of the research, water recovery starts from 500,000 Pa and becomes inefficient after 2,500,000 Pa pressure. Fritzman et al. [15] have stated that the ratio of Kw/m³ is 2 in the reverse osmosis method. Also, they have stated that Spain achieves 4.6% of all freshwater use (2,326 m³ per day) by the reverse osmosis method. This situation exemplifies the models of Israel, Cyprus, Malta, and Belgium, which are more water-scarce than Spain. Cardona et al. [16] have examined the natural gas energy consumption in SWRO systems and revealed that natural gas consumption is more efficient than other systems in freshwater production. Gurtler et al. [17] have combined the reverse osmosis method with the electrodialysis method. They have stated that by giving electricity to the saltwater with the electrodialysis method, they have reduced the salt solution ratio in the water by 1.5:1. Khawaji [18] has reviewed current R&D studies on desalination systems in Fujairah/Dubai. He has stated that reducing the cost of desalination systems can be achieved by hybrid systems. In addition, he has shown the world’s largest hybrid multistage flash and reverse osmosis system as an example. The World Health Organization (WHO) [19] has said that the following should be taken into account for purification purposes: exposed UV intensity level, pH, light absorption, the durability of the membrane in the filter, flow rate, watercolor, conductivity, local meteorological weather events, water turbidity, algal growth status, bacteria, microbiological organisms, chlorine, oxidation, and pressure. According to Caron et al. [20], the use of the reverse osmosis method has increased due to its lower cost compared to other methods. However, the membrane filters used in this method should
not let the algae pass from the filter. Unfortunately, they could not find evidence that the toxins left by the algae when filtered. This result has shown that monitoring sensors for detecting algae ASP and PSP toxins must be developed, and the reverse osmosis method may not be filtrated adequately in certain circumstances. Pangarkar et al. [21] have stated that although India constitutes 16% of the world population, it has only 4% as a freshwater resource. They also have stated that the water needed by India would probably be 1,450 km$^3$ in 2050 and the current water requirement in India is 1,086 km$^3$. They have mentioned the potential growth of the RO system that might help future India’s sustainability. Chungh et al. [22] have pointed out the necessity of the desalination process. They have stated that while only 1% of the Earth is covered with freshwater, the remaining left 97% is covered with saltwater. They have designed a freshwater generator system that can operate under low temperature and pressure, responding to this need. Stated that the water can be evaporated below the boiling point at low temperatures (40–80°C) and the low pressure brings lower costs. Giernalczyk and Herdzik [23] have studied freshwater treatment for sailing ships. Their research examined the 667 DWT, 94.7 meters long, 14 meters wide sailing ship named S/V Dar Młodzieży. They have calculated that the freshwater tank of the ship is 338.1 m$^3$, the daily freshwater consumption is 18.8 m$^3$, and the daily water treatment is 10.62 m$^3$. With the freshwater treatment device attached to the sailboat, the time for the ship to stop by the port for water and receive supply has been increased from approximately 18 days to 41 days. While the system’s installation cost is PLN 15,500 the water treatment cost per m$^3$ is calculated as PLN 5. Diaconu and Dragomir [24] have shown a high percentage of salt, metal oxides, silica, and a lot of debris would remain at the bottom of the boiler of freshwater generators working with boilers. They have stated that these molecules accumulated with possible neglect or leakage can quickly pass into the freshwater tank. They have reached the outcome that the corroded metal in the boiler might be a possible defect in the filtration. They have underlined that the first condition of a successful distillation is to pass through the right filter. Youssef et al. [25] have examined the existing desalination systems and reached the outcome that the multistage flash (MSF) system is the most inefficient freshwater treatment system according to the amount of energy consumed. They have also revealed that the humidification and dehumidification distillation (HDH) method has the lowest water consumption. Guler et al. [26] have investigated the desalination costs per cubic meter according to sea temperatures and salinity rates. They have found that the lesser salinity ratio is more effective than the higher temperature ratio in terms of the desalination process environment. Kumar and Kumar [27] have referred to wastes and flue gases at high temperatures as the negative effects of global warming. They have underlined the benefits of thermolectric generators on boilers. The benefits of this generator help reduce the greenhouse gas (GHG) factor by generating electricity, increasing efficiency, and reducing the demand, and it is the fuel cost of other natural gas power plants. They have produced a thermolectric generator by mixing a 1:10 ratio of petroleum jelly and petroleum wax. They have also pointed out that with the help of this system, the heat of the funnel of a vessel could be used as potential electrical energy with the necessary equipment connected to the ship. Güney [28] has reminded that all new vessels launched after 2017 must plant ballast water treatment systems, and existing vessels over 400 GT with permanent ballast tanks must have ballast water treatment systems by 2024 at the latest. Also, he has compared the brands of the existing ballast water treatment systems. Pecarevic et al. [29] have examined the role of the hydrocyclone, which is used in ballast water treatment systems. As a result of the research, they have concluded that the hydrocyclone has increased the treatment capacity in cubic meters per hour at a high rate in the ballast water treatment system. Vorkapic et al. [30] have divided ballast water treatment systems into three groups. They have examined D1, D2 + UV, and D2 + EC standards. For a true comparison of each system, a 54,335 DWT LPG ship with a 17,741 m$^3$ ballast tank has been selected as an example. They have calculated the annual costs of each system. Results have been found as the D1 system cost 4,368.96 USD, the D2 system cost 2,885.59 USD, and the D2 + EC system cost 623.61 USD. Yuksel et al. [31] have researched the seawater inlet temperature entering the freshwater generator. After the experiments, they observed that the efficiency of the produced freshwater increased with each degree increase from –273°C (absolute zero) to 30.83°C of temperature. However, they have observed that when the temperature rises above 30.83°C, the freshwater yield decreases very rapidly. Karabelas et al. [32] have analyzed the energy consumption in the reverse osmosis system. As a result of the data obtained, they have stated that the energy consumed per cubic meter to be produced is 2.37 kW/h in total and that each 10% increase in pressure at the seawater inlet will create an increase of 0.2 kW/h per m$^3$. Enescu [33] has researched methods to generate energy from stack heat to reduce energy consumption and increase efficiency in ship fittings. He stated that thermolectric generators work with 5–6% efficiency in flue waste-heat energies. He also stated that these generators, which can operate at temperatures up to 250°C and convert electrical energy, are one of the efficiency-increasing elements in recycling. He has stated that thermolectric generators can reach up to 10% efficiency due to recent developments in materials science. Toküş [34] has investigated the costs of standard D1 and D2 methods in the ballast water treatment methods determined by IMO and showed that the installation cost of the ballast water treatment system is €400,000. He also has underlined that the highest cost is not the cost of use but the investment costs. Hartanto et al. [35] have surveyed 67 maritime students returning after a 12-month long-term sea internship about the freshwater generator. The survey data obtained was evaluated in the SPSS program. After the following conclusion was reached, the differences in the pump of the freshwater generator affected the freshwater production efficiency positively by 39%, and changing the ejector positively affected the efficiency by 43.5%. Amaya-Vias et al. [36] have investigated the design of a simpler and less emissive desalination system. They have stated that the direct
contact spray assisted evaporation method increased the potable water rate up to 34%, improving the microbubble method in distillation. Alrowais et al. [37] have compared DCMD, AGMD, and WGMD water treatment configurations with different membrane filters in the 0.45 and 0.20 μm range on cruise ships. They have stated that the membrane with 0.45 μm holes has 99.99% salt filtration and can be a sustainable desalination method in passenger ships with the WGMD system.

When the literature research has been reviewed thoroughly, it has been seen that the existing studies mostly focused on passenger ships and shore-based desalination systems. This study, unlike other studies, has been aimed to select the most suitable desalination system for cargo vessels among the alternatives of “freshwater generator,” “reverse osmosis method,” and “adding a membrane filter if mechanical + UV ballast water treatment system available onboard.”

3. Methodology

Alternatives and criteria are determined based on the expert opinions by conducting several expert consultations. The alternatives are determined without leaving any room for other alternatives, since there are three different desalination methods that can be used at present, and other methods cannot be used on ships. The alternatives are selected as follows: alternative 1: freshwater generator, alternative 2: reverse osmosis method, and alternative 3: a mechanical+UV ballast water treatment system with an improved additional membrane filter.

The TOPSIS method is frequently preferred in the literature because it reveals the distances between the positive and negative ideal solutions. It is easy to use, understand, and interpret the results and is also simple in ordering the alternatives. The intuitionistic fuzzy extended version of the TOPSIS method is used in this study because it is possible to assign different importance to decision-makers, to see different results by giving different importance, and to be accepted by the literature in giving intuitionistic values. The alternatives and criteria are evaluated in line with the questionnaires answered by the experts and the alternatives are listed. The results and interpretations are provided in Section 6.

3.1. Intuitionistic Fuzzy TOPSIS Methodology

3.1.1. Intuitionistic Fuzzy Sets and Scale. In this study, intuitionistic fuzzy TOPSIS methodology is utilized based on the work of Shen et al. [38] in an intuitionistic fuzzy environment, which is a complex form of fuzzy sets [39] and TOPSIS [40]. The set of alternatives is \( A = \{ A_1, A_2, \ldots, A_m \} \), and the set of criteria is \( C = \{ C_1, C_2, \ldots, C_n \} \). The decision-making group is not equal and consists of \( \ell \) different decision-makers. In nonidentical decision-making groups, the relative importance of the decision-makers, therefore, differs from each other.

Intuitionistic fuzzy linguistic terms are used in the evaluation of decision-makers, which is given in Table 1 [41]. Also, Table 1 is reproduced from [42].

3.1.2. Expert Prioritization by Using Intuitionistic Fuzzy Scale. Decision-makers may have less or more expertise levels than other decision-makers due to their different experiences and knowledge. The weight vector of the decision-makers is \( \lambda = \{ \lambda_1, \lambda_2, \ldots, \lambda_\ell \} \) and \( \sum_{k=1}^{\ell} \lambda_k = 1 \), the weight vectors of decision-makers are applied as follows:

\[
\lambda = \frac{\lambda_k (\mu_k + \pi_k (\mu_k / \mu_k + \pi_k))}{\sum_{k=1}^{\ell} \lambda_k (\mu_k + \pi_k (\mu_k / \mu_k + \pi_k))}
\]

3.1.3. Intuitionistic Fuzzy TOPSIS Method. (1) First Step: After calculating the weight vectors of the decision-makers, the intuitionistic fuzzy decision matrix \( D = (\bar{a}_{ij})_{mn} \) \((i = 1, 2, \ldots, m; j = 1, 2, \ldots, n)\) is generated in the form of \( \bar{a}_{ij} = (\mu_{ij}, \pi_{ij}) \), where \( m \) represents alternatives and \( n \) represents criteria.

\[
D = (\bar{a}_{ij})_{mn} = \begin{bmatrix}
A_1 & A_2 & \cdots & A_m \\
\bar{a}_{11} & \bar{a}_{12} & \cdots & \bar{a}_{1n} \\
\bar{a}_{21} & \bar{a}_{22} & \cdots & \bar{a}_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\bar{a}_{m1} & \bar{a}_{m2} & \cdots & \bar{a}_{mn}
\end{bmatrix}
\]

(2) Second Step: Positive ideal solution is calculated based on \( \bar{a}_{j}^+ \), and let \( C^+, C^- \), and \( 1 \leq j \leq n \) be according to

\[
\bar{a}_{j}^+ = \begin{cases}
(\max 1 \leq i \leq m \{\mu_{ij}\}, \min 1 \leq i \leq m \{\nu_{ij}\}) = (\mu^*_j, \nu^*_j), & \text{if } C_j \in C^+,

(\min 1 \leq i \leq m \{\mu_{ij}\}, \max 1 \leq i \leq m \{\nu_{ij}\}) = (\mu^*_j, \nu^*_j), & \text{if } C_j \in C^-.
\end{cases}
\]

Table 1: Linguistic variables [41, 42].

| Linguistic terms |\( \mu \) |\( \nu \) |\( \pi \) |
|------------------|---------|---------|---------|
| Very good        | 0.75    | 0.10    | 0.15    |
| Good             | 0.60    | 0.25    | 0.15    |
| Moderate         | 0.50    | 0.50    | 0.00    |
| Bad              | 0.25    | 0.60    | 0.15    |
| Very bad         | 0.10    | 0.75    | 0.15    |
(3) **Third Step:** Negative ideal solution is calculated based on \( \bar{a}_j^- \), and let \( C^+, C^- \), and \( 1 \leq j \leq n \) be according to

\[
\bar{a}_j^- = \begin{cases}
(\text{min } 1 \leq i \leq m\{\mu_{ij}\}, \text{max } 1 \leq i \leq m\{v_{ij}\}) = (\mu_j^-, v_j^-), & \text{if } C_j \in C^+,
(\text{max } 1 \leq i \leq m\{\mu_{ij}\}, \text{min } 1 \leq i \leq m\{v_{ij}\}) = (\mu_j^+, v_j^+), & \text{if } C_j \in C^-.
\end{cases}
\] (4)

(4) **Fourth Step:** Positive intuitionistic fuzzy matrix \( D^+ \) is calculated as follows:

\[
D^+ = \begin{bmatrix}
C_1 & C_2 & \ldots & C_m \\
A_1 & (\bar{a}_{11}, \bar{a}_1) & (\bar{a}_{12}, \bar{a}_2) & \ldots & (\bar{a}_{1m}, \bar{a}_m) \\
& \vdots & \vdots & \ddots & \vdots \\
A_m & (\bar{a}_{m1}, \bar{a}_1) & (\bar{a}_{m2}, \bar{a}_2) & \ldots & (\bar{a}_{mn}, \bar{a}_n)
\end{bmatrix}_{mn}
\] (5)

The differences between two intuitionistic fuzzy numbers \( \alpha = (\mu_\alpha, \nu_\alpha) \) and \( \beta = (\mu_\beta, \nu_\beta) \) are calculated as follows:

\[
d(\alpha, \beta) = \sqrt{\frac{[\mu_\alpha(1 + 2/3\pi_\alpha(1 + \pi_\alpha)) - \mu_\beta(1 + 2/3\pi_\beta(1 + \pi_\beta))]^2 + [\nu_\alpha(1 + 2/3\pi_\alpha(1 + \pi_\alpha)) - \nu_\beta(1 + 2/3\pi_\beta(1 + \pi_\beta))]^2}{2}}
\] (6)

(5) **Fifth Step:** Negative intuitionistic fuzzy distance matrix \( (D^-) \) is calculated as follows:

\[
D^- = \begin{bmatrix}
C_1 & C_2 & \ldots & C_m \\
A_1 & (\bar{a}_{11}, \bar{a}_1) & (\bar{a}_{12}, \bar{a}_2) & \ldots & (\bar{a}_{1m}, \bar{a}_m) \\
& \vdots & \vdots & \ddots & \vdots \\
A_m & (\bar{a}_{m1}, \bar{a}_1) & (\bar{a}_{m2}, \bar{a}_2) & \ldots & (\bar{a}_{mn}, \bar{a}_n)
\end{bmatrix}_{mn}
\] (7)

According to Boran and Akay [43], \( \mu_\alpha \) and \( \nu_\alpha \) will be equal to \( [\mu_\alpha, \mu_\alpha + \pi_\alpha] \) and \( [\nu_\alpha, \nu_\alpha + \pi_\alpha] \) at any value.

(6) **Sixth Step:** Then, complex intuitionistic fuzzy distance matrices \( (D^* = D^- - D^+) \) are calculated as follows:

\[
D^* = \begin{bmatrix}
C_1 & C_2 & \ldots & C_m \\
A_1 & (Z_{11}^* \ \ Z_{12}^* \ \ \ldots \ \ Z_{1n}^*) \\
& \vdots & \vdots & \ddots & \vdots \\
A_m & (Z_{m1}^* \ \ Z_{m2}^* \ \ \ldots \ \ Z_{mn}^*)
\end{bmatrix}
\] (8)

\[
D^* = \begin{bmatrix}
A_1 & d(\bar{a}_{11}, \bar{a}_1) - d(\bar{a}_{11}, \bar{a}_1) & d(\bar{a}_{11}, \bar{a}_2) - d(\bar{a}_{11}, \bar{a}_2) & \ldots & d(\bar{a}_{11}, \bar{a}_m) - d(\bar{a}_{11}, \bar{a}_m) \\
& \vdots & \vdots & \ddots & \vdots \\
A_m & d(\bar{a}_{m1}, \bar{a}_1) - d(\bar{a}_{m1}, \bar{a}_1) & d(\bar{a}_{m1}, \bar{a}_2) - d(\bar{a}_{m1}, \bar{a}_2) & \ldots & d(\bar{a}_{m1}, \bar{a}_n) - d(\bar{a}_{m1}, \bar{a}_n)
\end{bmatrix}
\] (9)
(7) Seventh Step: Optimal weight $\omega^*_j$ for each criterion $C_j$ is calculated as follows:

$$\omega^*_j = \frac{\sum_{i=1}^{m} \sum_{k=1}^{n} |Z_{ij} - Z_{kj}|}{\sum_{j=1}^{n} \sum_{k=1}^{m} |Z_{ij} - Z_{kj}|}$$  \hspace{1cm} (10)

(8) Eighth Step: Weighted intuitionistic fuzzy distance for each alternative is calculated as follows:

$$D_i = \sum_{j=1}^{n} \omega^*_j z_{ij}^*$$ \hspace{1cm} \text{for } i = 1, 2, \ldots, m.  \hspace{1cm} (11)

(9) Ninth Step: Alternatives are ordered from highest to lowest according to $D_i$. The most suitable alternative is obtained.

3.1.4. Proposed Approach. This study utilizes intuitionistic fuzzy sets for selecting the best desalination method. As a novelty, we firstly employ expert prioritization for the IF-TOPSIS method in equation (1) by using intuitionistic fuzzy sets in Table 1, importance and the methods for expert prioritization are given [44]. The expert weights are distributed to their judgments in order to get more accurate results. Then the IF-TOPSIS method is applied. The steps of the IF-TOPSIS method for the most suitable desalination system on commercial vessels are given in Figure 1.

4. Particulars of Criteria and Alternatives

Three alternatives and seven criteria are determined by the literature review and expert consultations. As a result of the questionnaires that are answered by 13 different field experts, the relevant weights are calculated. The hierarchy of the proposed problem is given in Figure 2.

The criteria and their definitions are given in Table 2.

The alternatives and their definitions for the proposed problem are given in Table 3.

5. Application

5.1. Step-by-Step Application of IF-TOPSIS. Since the expertise levels of the decision-makers for the alternatives and criteria are different, the intuitionistic fuzzy TOPSIS method is implemented based on the opinions of the decision-makers, and the alternatives are evaluated by assigning different importance levels.

5.1.1. First Step. The weights of decision-makers are calculated according to equation 1. Table 4 is reproduced from Yıldırım’s work [45].

The data obtained from the questionnaires were multiplied by the percentage of influence of each decision-maker on the result. The combined group decision-making values...
Table 2: Definition of criteria and subcriteria.

| Main criteria     | Subcriteria                                      | Description                                                                                                                                                                                                 |
|-------------------|--------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Cost criterion    | System installation cost (C1)                   | It is the infrastructure cost required for the installation of the system. It varies according to the complexity of the system and the amount of freshwater to be obtained.                                         |
|                   | System operation cost (C2)                       | Distillation and filtration costs will be compared mutually. The operating costs of distillation with the heat coming from the chimney and the electricity-consuming filter pump coming from the alternator will be compared. |
| Safety criterion  | Environment pollution risk of the system (C3)    | The risks of a possible failure, leakage into the sea, or polluting the sea of the systems will be compared.                                                                                                    |
|                   | Risk to human health (C4)                        | In a possible unusual, emergency and/or a leak into the freshwater tank, the risks of affecting the human health of the systems will be mutually evaluated.                                                      |
|                   | Easiness of maintenance (C5)                     | Every freshwater tank needs to be cleaned, and every freshwater treatment system needs to be maintained at regular intervals. The criterion of easiness of maintenance will be compared for each alternative. |
|                   | User-friendliness (C6)                           | The ease of use of the system is very important and some long-term ballast operations can be tiring. In this criterion, operation time, difficulty, and easiness will be compared.                           |
| Technical criterion (TC) | Easiness for ship deployment (C7) | Deployment of the system on the ship plays a very effective role in system selection. In some cases, the system that does not comply with the relevant ship design or does not have enough free space for the installation of the system on the ship prevents the installation of the freshwater treatment system to be selected in the future. The criteria of easiness for ship deployment, having sufficient space, being suitable for installation in design, and ease of installation are highly important criteria for future system deployment. |

Table 3: The alternatives and their definitions.

| Alternative                                      | Description                                                                                                                                                                                                                                                                                                                                 |
|--------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Freshwater generator (A1)                        | The freshwater generator is a desalination system that is permanently used on ships that do not make short voyages and do not supply freshwater from the port. This system is also known as the evaporator. This system, which boils seawater and distills it with high energy consumption, is used conventionally on ships. This method, which can provide compression with high pressure by means of a pump, filters the freshwater and removes all other beneficial and harmful components, especially sodium chloride, from seawater. Over time, the development of nanotechnology in membrane filters and the production of freshwater at high flow have made the reverse osmosis method attractive. |
| Reverse osmosis method (A2)                      | It is a very complex system, which was started to be used on ships in 2017. It contains UV radiation and hydrocyclones that kill harmful microorganisms that can be transported through ballast waters, especially filtration.                                                                                                                                 |
| Installation of a membrane filter in addition to existing mechanical + UV ballast water treatment systems (A3) | The question of removing the use of the conventional freshwater generator by installing an additional membrane filter on this mechanical system has been raised.                                                                                                                                                                                      |
obtained are shown in Table 5, with all three rows representing alternative 1, alternative 2, and alternative 3.

5.1.2. Second Step. The positive ideal solution set $\alpha_j^+$ is $\alpha_j^+ = (\alpha_{j1}^+, \alpha_{j2}^+, \alpha_{j3}^+, \alpha_{j4}^+, \alpha_{j5}^+, \alpha_{j6}^+, \alpha_{j7}^+)$. A positive intuitionistic fuzzy solution is obtained for each criterion by using equation (3) and is shown in Table 6.

5.1.3. Third Step. The negative ideal solution set $\alpha_j^-$ is $\alpha_j^- = (\alpha_{j1}^-, \alpha_{j2}^-, \alpha_{j3}^-, \alpha_{j4}^-, \alpha_{j5}^-, \alpha_{j6}^-, \alpha_{j7}^-)$. A negative intuitionistic fuzzy solution is obtained for each criterion by using equation 4 and is shown in Table 7.

5.1.4. Fourth Step. Using equation (5), the positive intuitionistic fuzzy distance matrix $D^+$ is obtained as follows:

\[
D^+ = \left( d(\alpha_j, \alpha_j^+) \right)_{3x7}
\]

Table 4: Grading the decision-makers with intuitionistic fuzzy linguistic variables and impact percentages of all decision-makers [45].

| Decision-maker | Years of expertise in desalination systems | Position | Degree | $\mu$ | $\nu$ | $\pi$ | Effective percentage on result (%) |
|----------------|------------------------------------------|----------|--------|-------|-------|-------|-----------------------------------|
| Expert 1       | 3                                        | Third officer | B.Sc. | 0.10  | 0.75  | 0.15  | 1.42                             |
| Expert 2       | 5                                        | Second officer | B.Sc. | 0.50  | 0.50  | 0.00  | 6.05                             |
| Expert 3       | 11                                       | Academician  | Ph.D. | 0.75  | 0.10  | 0.15  | 10.68                            |
| Expert 4       | 4                                        | Academician  | M.Sc. | 0.25  | 0.60  | 0.15  | 3.56                             |
| Expert 5       | 12                                       | First officer | B.Sc. | 0.75  | 0.10  | 0.15  | 10.68                            |
| Expert 6       | 7                                        | Academician  | Ph.D. | 0.60  | 0.25  | 0.15  | 8.54                             |
| Expert 7       | 10                                       | First officer | B.Sc. | 0.60  | 0.25  | 0.15  | 8.54                             |
| Expert 8       | 8                                        | First officer | B.Sc. | 0.60  | 0.25  | 0.15  | 8.54                             |
| Expert 9       | 8                                        | Second officer | B.Sc. | 0.50  | 0.50  | 0.00  | 6.05                             |
| Expert 10      | 8                                        | First officer | B.Sc. | 0.60  | 0.25  | 0.15  | 8.54                             |
| Expert 11      | 14                                       | Master       | B.Sc. | 0.75  | 0.10  | 0.15  | 10.68                            |
| Expert 12      | 5                                        | Second officer | B.Sc. | 0.50  | 0.50  | 0.00  | 6.05                             |
| Expert 13      | 5                                        | Second officer | B.Sc. | 0.50  | 0.50  | 0.00  | 6.05                             |

Table 5: Forming of intuitionistic fuzzy decision matrix.

| C1 | C2 | C3 |
|----|----|----|
| $\mu$ | $\nu$ | $\pi$ | $\mu$ | $\nu$ | $\pi$ | $\mu$ | $\nu$ | $\pi$ |
| 0.738 | 0.116 | 0.150 | 0.105 | 0.734 | 0.150 | 0.712 | 0.148 | 0.150 |
| 0.100 | 0.750 | 0.150 | 0.517 | 0.461 | 0.036 | 0.116 | 0.735 | 0.150 |
| 0.215 | 0.644 | 0.150 | 0.480 | 0.511 | 0.016 | 0.125 | 0.731 | 0.150 |

Table 6: Positive ideal solution of each criterion.

| $\alpha_j^+$ | $\mu$ | $\nu$ | $\pi$ |
|--------------|-------|-------|-------|
| $\alpha_{j1}^+$ | 0.735 | 0.116 | 0.146 |
| $\alpha_{j2}^+$ | 0.517 | 0.461 | 0.022 |
| $\alpha_{j3}^+$ | 0.712 | 0.148 | 0.140 |
| $\alpha_{j4}^+$ | 0.691 | 0.191 | 0.117 |
| $\alpha_{j5}^+$ | 0.738 | 0.160 | 0.101 |
| $\alpha_{j6}^+$ | 0.544 | 0.422 | 0.034 |
| $\alpha_{j7}^+$ | 0.738 | 0.160 | 0.101 |

Table 7: Negative ideal solution of each criterion.

| $\alpha_j^-$ | $\mu$ | $\nu$ | $\pi$ |
|--------------|-------|-------|-------|
| $\alpha_{j1}^-$ | 0.100 | 0.750 | 0.150 |
| $\alpha_{j2}^-$ | 0.105 | 0.734 | 0.160 |
| $\alpha_{j3}^-$ | 0.116 | 0.738 | 0.146 |
| $\alpha_{j4}^-$ | 0.116 | 0.738 | 0.146 |
| $\alpha_{j5}^-$ | 0.100 | 0.750 | 0.150 |
| $\alpha_{j6}^-$ | 0.100 | 0.750 | 0.150 |
| $\alpha_{j7}^-$ | 0.100 | 0.750 | 0.150 |

\[
D^+ = \left( d(\alpha_j, \alpha_j^+) \right)_{3x7} = A_1 \begin{bmatrix} 0.002 & 0.380 & 0.004 & 0.005 & 0.002 & 0.425 & 0.002 \\ 0.708 & 0.005 & 0.659 & 0.619 & 0.649 & 0.007 & 0.673 \\ 0.585 & 0.044 & 0.650 & 0.484 & 0.673 & 0.193 & 0.562 \end{bmatrix}
\]
5.1.5. **Fifth Step.** Using equation (7), the negative intuitionistic fuzzy distance matrix \( D^- \) is obtained as follows:

\[
D^- = (d(a_{ij}, a^-_j))_{3 \times 7} = A_1 \begin{bmatrix}
0.709 & 0.005 & 0.660 & 0.620 & 0.674 & 0.000 & 0.674 \\
0.000 & 0.383 & 0.002 & 0.002 & 0.024 & 0.426 & 0.000 \\
0.123 & 0.339 & 0.008 & 0.133 & 0.000 & 0.232 & 0.111 \\
\end{bmatrix}
\]  

5.1.6. **Sixth Step.** Complex intuitionistic fuzzy distance matrices are calculated by the help of \( D^* = (D^- - D^+) \), which is expressed in equations (8) and (9).

\[
D^* = (Z^*_i)_{3 \times 7} = A_1 \begin{bmatrix}
0.707 & -0.375 & 0.656 & 0.615 & 0.672 & -0.425 & 0.672 \\
-0.708 & 0.378 & -0.657 & -0.617 & -0.624 & 0.419 & -0.673 \\
-0.462 & 0.295 & -0.642 & -0.351 & -0.673 & -0.040 & -0.450 \\
\end{bmatrix}
\]

5.1.7. **Seventh Step.** According to (10), the optimal weights of the criteria are determined.

\[
\sum_{i=1}^{3} \sum_{k=1}^{7} |Z_{i1} - Z_{k1}| = 5.663,
\]

\[
\sum_{i=1}^{3} \sum_{k=1}^{7} |Z_{i2} - Z_{k2}| = 3.012,
\]

\[
\sum_{i=1}^{3} \sum_{k=1}^{7} |Z_{i3} - Z_{k3}| = 5.253,
\]

\[
\sum_{i=1}^{3} \sum_{k=1}^{7} |Z_{i4} - Z_{k4}| = 4.929,
\]

\[
\sum_{i=1}^{3} \sum_{k=1}^{7} |Z_{i5} - Z_{k5}| = 5.381,
\]

\[
\sum_{i=1}^{3} \sum_{k=1}^{7} |Z_{i6} - Z_{k6}| = 4.060,
\]

\[
\sum_{i=1}^{3} \sum_{k=1}^{7} |Z_{i7} - Z_{k7}| = 5.381.
\]

5.1.8. **Eighth Step.** Based on (11), the weighted intuitionistic fuzzy distance is calculated for each alternative \( D^*_i \) value.

\[
\bar{D}_1 = \sum_{j=1}^{7} \omega^*_i z^*_ {ij} = 0.441,
\]

\[
\bar{D} = \sum_{j=1}^{7} \omega^*_i z^*_ {ij} = -0.435,
\]

\[
\bar{D}_3 = \sum_{j=1}^{7} \omega^*_i z^*_ {ij} = -0.378.
\]
5.1.9. Ninth Step. Intuitionistic fuzzy distance values for each alternative found in the eighth step are ordered from the highest to the lowest. The highest $\bar{D}_i$ score was determined as the most suitable alternative among the alternatives. In Table 8, the result of the most suitable desalination system alternatives is compared based on the seven criteria and shown as follows.

We implemented several different techniques to compare the rankings as given in Table 9. We see that the rankings are exactly the same with fuzzy AHP methods. It also shows the conventional TOPSIS and the proposed IF-TOPSIS are different that is normal since the IF-TOPSIS method is completely different in terms of its methodology. Its superiorities are given in the study of Shen [38].

There are other models in the literature related to TOPSIS. According to Akram et al. [51] research, complex spherical fuzzy TOPSIS (CSF-TOPSIS) shows the characteristics of complex spherical fuzzy sets with the TOPSIS method. CSF sets include the trend to cover both aspects of information related to fulfilment, shortage, and displeasure nature of human decisions. Another model, which has been shown in Akram et al. [52] research, shows that the Pythagorean fuzzy hybrid order of preference by similarity to an ideal solution (PFH-TOPSIS) approach calculates the distances of failure modes from the Pythagorean fuzzy PIS and Pythagorean fuzzy NIS. To judge failure modes, the Pythagorean fuzzy hybrid elimination and choice translating reality I (PFH-ELECTRE I) method constructs Pythagorean fuzzy concordance and Pythagorean fuzzy discordance matrices. The relevant model with the IF-TOPSIS model has been shown in Akram et al. [53] research. In the complex spherical fuzzy TOPSIS (CPF-TOPSIS) method, the allocated alternatives have been compared according to being superior and inferior to other alternatives based on score or accuracy by linguistic terms. In complex Pythagorean fuzzy concordance and discordance, sets compare the alternatives being dominant to the rest of the alternatives on score degree, accuracy degree, and indeterminacy. In the CPF-ELECTRE I method, outranking decision graphs are shown to obtain the best alternative. The structure of both methods illustrates with the help of flow charts. According to Akram et al. [54], a comparison of bipolar fuzzy TOPSIS (BF-TOPSIS) and bipolar fuzzy ELECTRE I (BF-ELECTRE-I) have been explained. The graphically presented methods visualize the viability, suitability, and achievability of the diagnostic process. While the BF-TOPSIS gives us one disease as diagnosis, BF-ELECTRE-I gives the set of diseases as a diagnosis. Moreover, the comparison analysis shows that diagnostic process is more reliable and precise.

### Table 9: Ranking of the most suitable desalination systems.

|                    | Fuzzy AHP (Chang) [48] | Fuzzy AHP (Buckley) [49] | Conventional TOPSIS [50] | IF-TOPSIS [39] |
|--------------------|------------------------|--------------------------|---------------------------|----------------|
| Value              | Rank                   | Value                    | Rank                      | Value          | Rank       |
| A1                 | 40.39%                 | 1                        | 59.94%                    | 1              | 0.911      | 1          |
| A2                 | 36.04%                 | 2                        | 23.65%                    | 2              | 0.793      | 3          | -0.378     | 2          |
| A3                 | 23.57%                 | 3                        | 16.41%                    | 3              | 0.826      | 2          | -0.435     | 3          |

5.2. Analysis of Results and Discussion. In this study, we embedded the expert prioritization concept based on the study of Yıldırım [45] as given in equation (1). We also tested other similar formulas such as the weighted product model (WPM) is a popular multicriteria decision analysis [46, 47] such as for $k = 1, 2, 3, \ldots, n$.

$$P(M_j) = \prod_{j=1}^{n} (M_{kj})^{w_j}. \quad (18)$$

However, this formula is not suitable for our problem because of the value of the linguistic expression of "Moderate", value is 0 and as it can be easily seen that 0 value makes all calculations equal to 0.

We implemented several different techniques to compare the rankings as given in Table 9. We see that the rankings are exactly the same with fuzzy AHP methods. It also shows the conventional TOPSIS and the proposed IF-TOPSIS are different that is normal since the IF-TOPSIS method is completely different in terms of its methodology. Its superiorities are given in the study of Shen [38].

### 6. Conclusions and Recommendations

Freshwater is the main source of life for the crew in commercial vessels. The importance of production methods in freshwater and its energy efficiency has been increasing day by day. The ever-tightening MARPOL Annex VI and flag state protocols and the inspections on NOx and SOx gases put pressure on the shipowners about the environmental damage caused by the vessel emissions. Ecological and efficiency concerns in the maritime environment and the recent developments in ballast water treatment systems have raised a new question: "whether the new water treatment systems already planted on vessels can be used as desalination systems instead of old conventional freshwater generators?"

According to literature, there are similar studies in the literature related to future desalination systems on vessels. Tomaszewka et al. [55] investigated the "treatment of bilge water with reverse osmosis and UV methods" and stated that the water obtained completely removed from the oil with the reverse osmosis and UV system. Jadmiko et al. [56] investigated a possible photovoltaic freshwater treatment system with the reverse osmosis system on the roll-on/roll-off passenger (RO-PAX) vessels and stated that it can be discussed whether the reverse osmosis system is economical but only with the help of installed solar separators and batteries on vessels. There are other similar issues in the literature but the question of whether the ballast water treatment system can be used instead of the conventional freshwater generator system or not has not been questioned. Lu et al. [57] have investigated whether the reverse osmosis method can be used in nonballast vessels. They stated that using the reverse osmosis method on "vessels without ballast tanks" would save more on spending and provide a robust water supply.
As a result of the literature research, it has been revealed that the current desalination on vessels research mostly focused on passenger ships due to high passenger capacity and excessive water consumption. Apart from the other studies in the literature, in this study, the most suitable desalination system has been investigated in nonpassenger vessels and limited to commercial vessels other than passenger ships.

To solve the question, the questionnaire has been carried out by taking the opinions of thirteen experts in both desalination and maritime research or job area. In these questionnaires, it has been asked from field experts to compare three different alternative desalination methods that could be placed on commercial vessels. The questionnaires have been carried out by pairwise comparison of these three alternatives according to seven different criteria to reach the most suitable desalination system. As the expertise levels of the decision-makers for the alternatives and criteria are different, an improved intuitionistic fuzzy TOPSIS method is implemented based on the opinions of the decision-makers, and the alternatives are evaluated by assigning different importance levels. As a result of the data obtained, the most suitable desalination method has been ranked as follows: freshwater generator (0.441) > installation of additional membrane filters to the existing mechanical+ UV ballast water treatment system on the ship (–0.378) > reverse osmosis method (–0.435). The order of the criteria is the system’s risk to human health (34.62%) > the environment pollution risk of system (20.41%) > system operation cost (18.34%) > system installation cost (9.42%) > easiness for ship deployment (7.35%) > easiness of maintenance (6.01%) > user-friendliness (3.81%). According to the results, it has been concluded that the rankings of the results obtained from each methodology have been compatible with each other.

According to the obtained results, the conventional freshwater generator still maintains its current value. Another remarkable situation has emerged among the alternatives. The findings revealed that the alternative of “installing additional membrane filters to the mechanical+ UV ballast water treatment system existing on the vessel” is more suitable than the “reverse osmosis method” alternative. In the study, the results have been interpreted as follows: due to the requirement of a ballast water treatment system on vessels with an International Oil Pollution Prevention Certificate (IOPP) after 2017, in commercial vessels that do not have passengers, the RO systems can be replaced with a “ballast water treatment system” in the future.

Results have also been answered yes to the question of whether the existing reverse osmosis systems can be integrated with the ballast water treatment system in passenger ships. The reason why the freshwater generator ranks first in the alternative ranking is due to the simple fact of the reverse osmosis system, which has a higher energy consumption initially. The RO system can help reduce the cost by producing high flow rate water dramatically. Although the RO system is quite reliable and cheap and requires low maintenance for the seawater desalination process, the RO system only depends on the high flow of water rate. This high flow of volume production makes this system only suitable for crowded commercial vessels or onshore facilities. Other than military/service or cruise vessels, this system has a lot of other downsides, with respect to its benefits in m³/ per capita. Also, when it is compared to the freshwater generator, there is a great threat to the marine environment and ecology due to the marine outfall of waste high-level brine water into the sea.

In the following studies, it has been kindly recommended to increase the number of alternatives by adding other desalination methods, such as “multistage flash distillation” and “electrodialysis water treatment methods,” and extensive research of RO systems with downsides and dangers to nature with countermeasures. Also, it has been recommended to increase the number of criteria by creating new criteria such as “green energy consumption in the system” and contribute to the literature by adding other multicriteria decision-making methodologies such as BF-ELECTRE I, CPF-ELECTRE I, PFH-ELECTRE I, CSF-TOPSIS, or other newly constructed models.

### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

### Additional Points

Expert prioritization is employed for the intuitionistic fuzzy TOPSIS method. The intuitionistic fuzzy scale is used for expert prioritization. The most suitable desalination system for commercial vessels is selected among others. A comparison of the values of other methods is provided.

### Conflicts of Interest

The authors declare that they have no conflicts of interest.

### References

[1] N. M. Wade, “Technical and economic evaluation of distillation and reverse osmosis desalination processes,” Desalination, vol. 93, no. 1-3, pp. 343–363, 1993.
[2] B. Van der Bruggen and C. Vandezande, “Distillation vs. membrane filtration: overview of process evolutions in seawater desalination,” Desalination, vol. 143, no. 3, pp. 207–218, 2002.
[3] R. Mulić and I. Jerončić Tomić, “Supplying ships with safe drinking-water,” International Maritime Health, vol. 71, no. 2, pp. 123–128, 2020.
[4] M. Oldenburg, U. Huesing, M. Kalkowski, X. Baur, and K. Schleich, “Chemical contamination of potable water in ship tanks,” International Maritime Health, vol. 58, no. 1-4, pp. 79–91, 2007.
[5] A. Martinez-Lopez, A. Ruiz-Garcia, and I. Perez, “Social cost benefit analysis of port handling plans for Annex IV waste of MARPOL: a case study in las palmas port,” Sustainability, vol. 12, no. 6, p. 2382, 2020.
[6] W. R. Batista, F. C. Fernandes, C. C. Lopes, R. S. Lopes, W. Miller, and G. Ruiz, “Which ballast water management
system will you put aboard? Remnant anxieties: a mini-review,” *Environments*, vol. 4, no. 3, 2017.

[7] D. A. Wright, “Compliance assessment for the ballast water convention: time for a re-think? A U.K. case study,” *Journal of Marine Engineering & Technology*, vol. 20, no. 7, pp. 1–8, 2018.

[8] N. B. Petersen, T. Madsen, M. A. Glaring, F. C. Dobbs, and N. O. G. Jørgensen, “Ballast water treatment and bacteria: analysis of bacterial activity and diversity after treatment of simulated ballast water by electrochlorination and UV exposure,” *The Science of the Total Environment*, vol. 648, pp. 408–421, 2019.

[9] O.-K. Hess-Erga, J. Marenco-Andres, O. Enger, and O. Vadsøen, “Microorganisms in ballast water: disinfection, community dynamics, and implications for management,” *The Science of the Total Environment*, vol. 657, pp. 704–716, 2019.

[10] E. Lakshmi, M. Priya, and V. S. Achari, “An overview on the treatment of ballast water in ships,” *Ocean & Coastal Management*, vol. 199, p. 105296, 2021.

[11] S. Ilham, O. Y. Al-Najdi, O. A. Hamed, G. Jun, and H. Chung, “Energy cost comparison between MSF, MED and SWRO: case studies for dual purpose plants,” *Desalination*, vol. 397, pp. 126–137, 2016.

[12] P. Glueckstern and M. Priel, “Advanced concept of large seawater desalination systems for Israel,” *Desalination*, vol. 119, no. 1-3, pp. 33–45, 1998.

[13] J. S. Choi, “Development of the fresh water generator,” *Energy Engineering Journal*, vol. 8, no. 4, pp. 546–552, 1999.

[14] L. Song, J. Y. Hu, W. J. Ng, M. Elimelech, and M. Will, “Performance limitation of the full-scale reverse osmosis process,” *Journal of Membrane Science*, vol. 214, pp. 239–244, 2003.

[15] C. Fritzman, J. Löwenberg, and T. M. Wittgens, “State of art of reverse osmosis desalination,” *Desalination*, vol. 216, no. 1-3, pp. 1–76, 2007.

[16] E. Cardona, A. Piacentino, and F. Marchese, “Performance evaluation of CHP hybrid seawater desalination plants,” *Desalination*, vol. 205, no. 1-3, pp. 1–14, 2007.

[17] B. K. Gurtler, T. A. Vetter, E. M. Perdue, E. Ingall, J.-F. Koprivnjak, and P. H. Piromma, “Combining reverse osmosis and pulsed electrical current electrodialysis for improved recovery of dissolved organic matter from seawater,” *Journal of Membrane Science*, vol. 332, no. 2, pp. 328–336, 2008.

[18] A. D. Khawaji, I. K. Kutubkhanah, and J. M. Wie, “Advances in seawater desalination technologies,” *Desalination*, vol. 221, no. 1-3, pp. 47–69, 2008.

[19] World Health Organization, *Guidelines for Drinking-Water Quality*, pp. 103–105, Geneva, 3rd ed edition, 2008.

[20] D. A. Caron, M.-E. Garneau, E. Seubert et al., “Harmful algae and their potential impacts on Desalination operation off southern California,” *Water Research*, vol. 44, no. 2, pp. 385–416, 2010.

[21] B. L. Pangarkar, M. G. Sane, and M. Guddad, “Reverse osmosis and membrane distillation for desalination of groundwater: a review,” *ISRN Materials Science*, vol. 2011, pp. 1–9, Article ID 523124, 2011.

[22] H. Chung, S. Wibowo, B. Fajar, Y. Shin, and H. Jeong, “Study on low pressure evaporation of fresh water generation system model,” *Journal of Mechanical Science and Technology*, vol. 26, no. 2, pp. 421–426, 2012.

[23] M. Giernalczyk and P. Herdzik, “The analysis of possible methods of providing fresh water for sailing vessels based on the example of S/V dar młodzięzy,” *Journal of Kones*, vol. 20, no. 1, pp. 95–102, 2013.

[24] N. Diaconu and S. Dragomir, “Performant installation for purification and desalination of sea water for cruise ship,” *Mechanical Testing and Diagnosis*, vol. 4, no. 2, pp. 23–30, 2014.

[25] P. G. Youssef, R. K. Al-Dadah, and S. M. Mahmoud, “Comparative analysis of desalination technologies,” *Energy Procedia*, vol. 61, pp. 2604–2607, 2014.

[26] E. Güler, E. G. Onkal, M. Celen, and E. H. San, “Cost analysis of seawater desalination using an integrated reverse osmosis system on a cruise ship,” *Global NEST Journal*, vol. 17, no. 2, pp. 389–396, 2015.

[27] N. Kumar and S. Kumar, “Waste heat recovery management using thermoelectric generator system,” *International Journal of Advanced Technology in Engineering and Science*, vol. 5, no. 7, pp. 223–234, 2017.

[28] C. B. Güney, “IMO ballast suyu sözleşmesi’ne göre gemilere balast suyu yönetimi ve güncel değişiklikler,” *GİDB Dergi*, vol. 12, pp. 21–36, 2018.

[29] M. Pečarević, J. Mikuš, I. Prusina, H. Juretić, A. Bratoš Cetinić, and M. Brailo, “New role of hydrocyclone in ballast water treatment,” *Journal of Cleaner Production*, vol. 188, pp. 339–346, 2018.

[30] A. Vorkapic, R. Radonja, and D. Zec, “Cost efficiency of ballast water treatment systems based on ultraviolet irradiation and electrochlorination,” *Promet - Traffic & Transportation*, vol. 30, no. 3, pp. 343–348, 2018.

[31] O. Yüksel, Y. Gülmez, O. Konur, S. A. Korkmaz, A. Erdoğan, and C. Ö. Colpan, “Energy analysis of a vacuum fresh water generator on a commercial vessel,” *Proceedings of the 7th global Conference on global warming (GCWW-2018), ižmir, Turkey*, 2018.

[32] A. J. Karabelas, C. P. Koutsou, M. Kostoglou, and D. C. Sioutopoulos, “Analysis of specific energy consumption in reverse osmosis desalination processes,” *Desalination*, vol. 431, pp. 15–21, 2018.

[33] D. Enescu, “Thermoelectric energy harvesting: basic principles and applications,” *Green Energy Advances*, Intechopen, vol. 1, pp. 1–29, 2019.

[34] M. Tokus, “Kuru yük gemisi ballast suyu arıtma sistemi entegrasyonu ve yasam döngüsü maliyet analizi,” *Journal of Maritime Engineering Science*, vol. 7, no. 3, pp. 196–210, 2019.

[35] H. Hartanto, A. Tjahono, O. Wahyuni, and E. Wibowo, “Factors affecting the performance of fresh water generator in commercial vessel,” *TEM Journal*, vol. 9, no. 1, pp. 19–24, 2020.

[36] D. Amaya-Vías, E. Nebot, and J. A. López-Ramírez, “Comparative studies of different membrane distillation configurations and membranes for potential use on board cruise vessels,” *Desalination*, vol. 429, pp. 44–51, 2018.

[37] R. Alrowais, C. Qian, M. Burhan, D. Ybyraiymkul, M. W. Shahzad, and K. C. Ng, “A greener seawater desalination method by direct-contact spray evaporation and condensation (DCSEC): Experiments,” *Applied Thermal Engineering*, vol. 179, Article ID 115629, 2020.

[38] F. Shen, X. Ma, Z. Li, Z. Xu, and D. Cai, “An extended intuitionistic fuzzy topsis method based on a new distance measure with an application to credit risk evaluation,” *Information Sciences*, vol. 428, pp. 105–119, 2018.

[39] L. A. Zadeh, “Fuzzy sets, fuzzy logic, and fuzzy systems: selected papers by Lotfi A Zadeh,” *Advances in Fuzzy Systems – Application and Theory*, vol. 6, pp. 394–432, 1996.
[40] Y. M. Wang and T. M. S. Elhag, "Fuzzy TOPSIS method based on alpha level sets with an application to bridge Risk assessment," *Expert Systems with Applications*, vol. 31, no. 2, pp. 1–11, 2006.

[41] B. Efe, F. E. Boran, and M. Kurt, "Sezgisel bulanık TOPSIS yöntemi kullanılarak ergonomik ürün konsept seçimi," *Süleyman Demirel Üniversitesi Mühendislik Bilimleri ve Tasarım Dergisi*, vol. 3, no. 3, pp. 433–440, 2015.

[42] H. Biderci and B. Canbaz, "Ergonomic room selection with intuitive fuzzy TOPSIS method," *Procedia Computer Science*, vol. 158, pp. 58–67, 2019.

[43] F. E. Boran and D. Akay, "A biparametric similarity measure on intuitionistic fuzzy sets with applications to pattern recognition," *Information Sciences*, vol. 255, pp. 45–57, 2014.

[44] B. Şahin and D. Yazır, "An analysis for the effects of different approaches used to determine expertise coefficients on improved fuzzy analytical hierarchy process method," *J. Fac. Eng. Archit. Gazi Univ.*, vol. 34, no. 1, pp. 89–102, 2019.

[45] B. F. Yıldırım, "Kredi kartı platformlarının sezgisel bulanık TOPSIS yöntemi kullanılarak değerlendirilmesi," *BDDK Bankacılık ve Finansal Piyasalar Dergisi*, vol. 13, no. 1, pp. 37–58, 2019.

[46] E. Triantaphyllou, *Multi-criteria Decision Making Methods: A Comparative Study*, 140 pages, Kluwer Academic Publishers, Dordrecht, 2000.

[47] E. Triantaphyllou and S. H. Mann, "An examination of the effectiveness of multi-dimensional decision-making methods: a decision-making paradox," *Decision Support Systems*, vol. 5, no. 3, pp. 303–312, 1989.

[48] D.-Y. Chang, "Applications of the extent analysis method on fuzzy AHP," *European Journal of Operational Research*, vol. 95, pp. 649–655, 1996.

[49] J. J. Buckley, "Fuzzy hierarchical analysis," *Fuzzy Sets and Systems*, vol. 17, pp. 233–247, 1985.

[50] C.-L. Hwang and P. K. Yoon, "Multiple attribute decision making: methods and applications," *Lecture Notes in Mathematical Systems*, Springer-Verlag, New York, 1981.

[51] M. Akram, C. Kahraman, and K. Zahid, "Extension of TOPSIS model to the decision-making under complex spherical fuzzy information," *Soft Computing*, vol. 25, no. 7, pp. 10771–10795, 2021.

[52] M. Akram, A. Luqman, and J. C. R. Alcantud, "Risk evaluation in failure modes and effects analysis: hybrid TOPSIS and ELECTRE I solutions with Pythagorean fuzzy information," *Neural Computing & Applications*, vol. 33, pp. 5675–5703, 2021.

[53] M. Akram, H. Garg, and K. Zahid, "Extensions of ELECTRE-I and TOPSIS methods for group decision-making under complex Pythagorean fuzzy environment," *Iranian Journal of Fuzzy Systems*, vol. 17, no. 5, pp. 147–164, 2020.

[54] M. Akram and M. Arshad, "Bipolar fuzzy TOPSIS and bipolar fuzzy ELECTRE-I methods to diagnosis," *Computational and Applied Mathematics*, vol. 39, no. 7, pp. 1–21, 2020.

[55] M. Tomaszewska, A. Orecki, and K. Karakulski, "Treatment of bilge water using a combination of ultrafiltration and reverse osmosis," *Desalination*, vol. 185, no. 1, pp. 203–212, 2015.

[56] E. Jadmiko, T. B. Musriyadi, and D. N. Ahmad, "Technical-Economic analysis of photovoltaik reverse osmosis planning for fulfillment of fresh water system on ro-pax ship," *International Journal of Marine Engineering Innovation and Research*, vol. 1, no. 4, pp. 330–345, 2020.

[57] K.-T. Lu, H.-K. Lui, C.-T. Arthur Chen et al., "Using onboard-produced drinking water to achieve ballast-free management," *Sustainability*, vol. 13, no. 14, pp. 1–12, 2021.