Received: 07 December 2018 *Accepted: 05 February 2019* *DOI ID: 10.5505/jems.2019.72623*

Journal of ETA Maritime Science

JEMS JOURNAL

Corresponding Author: Kadir ÇİÇEK

Knowledge-Based Expert System on the Selection of Shipboard Wastewater Treatment Systems

Kadir ÇİÇEK

İstanbul Technical University, Maritime Faculty, Turkey
cicekk@itu.edu.tr; ORCID ID: https://orcid.org/0000-0002-9732-3361

Abstract

During the last 20 years, regulatory enforcements regarding with the protection of marine environment have been significantly increased. Especially, starting from 1 January 2010 a new regulation, consisting of waste water treatment plants in ships and new effluent limits, took effect. The new limits comprise a stricter review of prior limits. The strict reduction in the effluent limits for the treated wastewater discharged from ships intimates International Maritime Organization (IMO)'s intention to provide more severe control on wastewater discharges and to demand on installation wastewater treatment system that meet international requirements. Furthermore, the new limits constitute a further challenge for the manufacturing companies specified in design and manufacturing of waste water treatment systems. To way out from these points, this study focuses on development a knowledge-based expert system for selection of appropriate shipboard wastewater treatment system. Within this scope, the study proposes a hybrid approach combining AHP and TOPSIS under fuzzy environment. The three most commonly preferred shipboard wastewater treatment system types are examined and evaluated in terms of various design, operation and environment criteria.

Keywords: *Shipboard Wastewater Treatment System, AHP, TOPSIS, Fuzzy Logic, Knowledge-Based Expert System.*

Gemi Üzeri Pis Su Arıtma Sistemi Seçimine Yönelik Bilgi Tabanlı Uzman Sistemi

Öz

Son 20 yıl içerisinde, deniz çevresinin korunması ile ilgili yasal düzenlemeler önemli derecede artış göstermiştir. Özellikle, 1 Ocak 2010 yılında gemilerdeki pis su arıtma sistemlerinin atık su limitlerini düzenleyen yeni bir kural yürürlüğe girmiştir. Gemilerden tahliye edilen arıtılmış sular içerisindeki atık limitlerinin önemli derecede azalması ile beraber Uluslararası Denizcilik Örgütü (IMO) dikkatini atık su tahliyesini çok daha sıkı bir şekilde denetlemeye ve gemilere donatılan pis su arıtma sistemlerinin uluslararası gereksinimleri karşılamasına çevirmiştir. Dahası, yeni atık limitleri ile beraber üretici firmalar pis su arıtma sistemlerinin tasarımı ve üretimi ile ilgili pek çok ileri düzey zorluklar ile karşı karşıya kalmışlardır. İlgili gelişmeler çerçevesinde, bu çalışma ile gemiler için en uygun pis su arıtma ünitesinin seçimi üzerine bilgi tabanlı bir uzman sistemi geliştirilmesi üzerinde yoğunlaşılmıştır. Bu doğrultuda, bu çalışma AHP ve TOPSIS yöntemlerini bulanık tabanlı olarak birleştirerek karma bir yaklaşım önerisinde bulunmaktadır. Gemiler üzerinde yaygın olarak kullanılan 3 pis su arıtma sistemi belirlenerek, çeşitli tasarım, operasyon ve çevresel kriterlere göre değerlendirilmiştir.

Anahtar Kelimeler: *Gemi Pis Su Arıtma Sistemi, AHP, TOPSIS, Bulanık Mantık, Bilgi Tabanlı Uzman Sistemi.*

To cite this article: Çiçek, K. (2019). Knowledge-Based Expert System on the Selection of Shipboard Wastewater Treatment Systems. *Journal of ETA Maritime Science*, 7(2), 101-115.
To link to this article: https://dx.doi.org/10.5505/jems.2019.72623

1. Motivation on Study

Over the last forty years, the international concerns have been tremendously increased about the possible threats to the marine environment stem from the shipping industry. The adoption of the International Convention for the Prevention of Marine Pollution from Ships (MARPOL) can be accepted as a milestone on the prevention of marine environment caused by ship-based pollutants. The first version of MARPOL was accepted in 1973. Over the years, it has been significantly revised and it still forms the basis for the future on prevention of marine environment. Nowadays, the International Maritime Organization (IMO) works toward the concept of environmentally sound ships for the 21st Century through adopting new and stricter regulations. In the document published by North Atlantic Treaty Organization (NATO) in 2010 [1], the concept behind the environmentally sound ship is defined as; "a ship that could operate in any water body worldwide without causing significant adverse environmental impacts while complying with all applicable environmental regulations". Under the light of this definition, minimization of waste generation and appropriate treatment or disposal method for the wastes generated on board can be considered as crucial environmental issues in today's shipping industry. Nowadays, considerable research and development activities have been made to develop on-board capabilities for treating or disposing of ship-based solid and liquid wastes. Additionally, tremendous research efforts have been made to provide satisfactory solutions for treating blackwater and greywater generated on board ships.

The strict reduction in the effluent limits on treated ship wastewater intimates IMO's intention to provide stricter control on wastewater discharges and to demand on more comprehensive selection and installation progress of shipboard wastewater systems on part of the engineers and the ship-owners. To overcome the challenges in the strict restrictions of wastewater discharge, manufacturers concentrate on new researches in the design and manufacturing stages of wastewater treatment technologies. These technological improvement researches generate numerous type shipboard wastewater treatment systems (SWWTS); however, a various number of limitations on board ship, such as confined space available to install, operation and maintenance cost, limited man power, limited repair and maintenance time, and harsh environmental conditions rarify the selection of appropriate wastewater technologies for responsible stakeholders in shipping industry.

In order to support the decision-making process of actors in the shipping industry, it is necessary to use the advantages of decision-making techniques in the literature; however, there are only limited number of studies have been proposed in the literature to provide solution on SWWTS selection. At this insight, this study proposes a knowledge-based expert system integrated into a fuzzy environment to handle the vagueness and subjectivity in the selection problem. A knowledge-based expert system consists of a combination of the Fuzzy Analytic Hierarchy Process (F-AHP) and Fuzzy Technique for Order Preference by Similarity to Ideal Solution (F-TOPSIS) methods. F-AHP is used to determine weights of the criteria, and F-TOPSIS is used to systemic evaluation of alternatives on multiple criteria.

Within this direction, the rest of the paper is organized as follows; literature review on the studies related to the scope of this study is comprehensively executed in section 2. The introduction of the proposed methodology is followed out in section 3. An application of the methodology is given in section 4. In the final section, the results and the proceeds of the proposed knowledge-based expert system are examined.

2. Literature Review

In the literature, it is possible to find a large number of studies realized by different methods to process selection, design, and operation of the wastewater treatment systems for the land-based application and the need for such studies is increasingly growing. For instance, Balmer & Mattson [2] proposed a study to analyse the wastewater treatment plant operation cost. Additionally, in 2001, Sarkis and Weinrach [3] used the advantages of Data Envelopment Analysis (DEA) method to evaluate alternative wastewater treatment technologies. Operational cost savings and capital cost savings were considered as input factors, transuranic waste and low-level waste were considered as output factors in the study. Besides, Tsagarakis et al. [4] proposed a study aiming to help engineers to evaluate wastewater projects. A cost-effectiveness criterion was introduced to evaluate alternative wastewater treatment systems in the study. As an important example of application Multi- Criteria Decision Making (MCDM) techniques in wastewater treatment system selection, Büyüközkan et al. [5] introduced an integrated MCDM model in a fuzzy environment to evaluate wastewater treatment investment from the aspects of economic effectiveness, technical feasibility, and environmental regulation. Also, Sato et al. [6] made an evaluation on sewage treatment systems respect to the total annual cost. Additionally, Anagnostopoulos et al. [7] used one of the important MCDM techniques, Analytic Hierarchy Process, combined with fuzzy logic to select wastewater facilities at the prefecture level. In 2007, Zeng et al. [8] proposed a systematic approach structured on the integration of Analytic Hierarchy Process (AHP) and Grey Relational Analysis (GRA) for wastewater treatment alternatives selection. Also, Alsina et al. [9] developed a model on the decision- making process related to the multi-criteria evaluation of Wastewater Treatment Plant (WWTP) control strategies. De Foe et al. [10] described a simple multi-criteria approach for the selection of the best chemical for the treatment of urban wastewater. Alsina et al. [11] presented a study to integrate the environmental assessment and life cycle assessment for the correct assessment of wastewater treatment plants. Bottero et al. [12] compared the analytic hierarchy process and the analytic network process for the assessment of wastewater treatment systems. Karimi et al [13] adopted analytical hierarchy process and fuzzy analytical hierarchy process methods for the selection of most suitable wastewater treatment process. Kalbar et al. [14] analysed the four most commonly used wastewater treatment technologies for the treatment of municipal wastewater in India with the help of TOPSIS methodology. Ilangkumaran et al. [15] proposed a hybrid Multi-Criteria Decision Making (MCDM) methodology for the selection of wastewater treatment (WWT) technology for treating wastewater. Upadhyay [16] applied Analytical Hierarchy Process to compare sewage treatment plants in India.

On the other hand, there are only a few studies in maritime side related to the topics of process selection, design, and operation of waste-water treatment systems. One of these studies is introduced by Demboski et al. [17] in 1997. In the study, the authors made an evaluation of US-Navy shipboard sewage and grey water systems. Additionally, in 2003, Eley & Morehouse [18] focused on the evaluation of new technology for shipboard wastewater treatment. Also, the guidelines published by the International Council of Marine Industry Association regarding the introduction of the alternative wastewater treatment systems [19] can be given another example document.

Respect to the literature review, the following findings can be explained:

i) There is a big gap in the literature related to the shipboard wastewater treatment system selection problem.
ii) MCDM techniques are commonly used in Wastewater Treatment System (WWTS) selection problems.
iii) Lack of information, uncertainty, and ambiguity in the selection problems mostly solved with the adoption of fuzzy logic.

Under the lights of these findings, this study focuses on the development of a knowledge-based expert system on SWWTS selection. The proposed knowledge-based expert system is explained in following section.

3. Proposed Methodology

MCDM methods provide notable solutions in a vast amount of problems in almost all industrial fields with their advantageous features [20]. Specifically, AHP method was defined as one of the most outstanding MCDM in the literature proposed by Thomas Saaty in 1980 [21]. In compare to other MCDM methods, AHP method has been successfully applied in many practical decision-making problems [22]. In addition to AHP Method, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is another most popular MCDM method developed by Hwang and Yoon in 1981 [23] which is based on choosing the best alternative. To eliminate the uncertainty, ambiguity and lack of information shortcomings in the selection problem using the classical AHP and TOPSIS methods with its ordinary (numerical) comparison grades do not seem possible. At that point adoption of fuzzy logic into the classical MCDM methods helps researchers to minimize the aforementioned shortcomings in the selection problems. In this direction, the study proposes a hybrid methodology with the combination of AHP and TOPSIS methods under fuzzy environment to constitute a knowledge-based expert system on SWWTS selection problem. Theoretical descriptions of the methods are described in the following subsections.

3.1. Fuzzy AHP (F-AHP)

In the literature, it is possible to find various extended version of AHP method under a fuzzy environment that propose systematic approaches. This study concentrates on a F-AHP approach introduced by Chang in 1992 [24]. Chang's extent analysis method on F-AHP uses triangular fuzzy numbers for pairwise comparison scale and depends on the degree of possibilities of each criterion.

In the proposed knowledge-based expert system, a Triangular Fuzzy Number (TFN), which can be represented as M = (l, m, u), where $l \leq m \leq u$, is used. The parameters (l) and (u) represent the lower and upper value of fuzzy number M respectively and parameter (m) represents the modal value. Triangular type membership function of M fuzzy number can be described as in Eq. (1) [25].

$$\mu_M(x) = \begin{cases} 0, & x < l \\ \dfrac{x-l}{m-l}, & l \leq x \leq m \\ \dfrac{u-x}{u-m}, & m \leq x \leq u \\ 0, & x > u \end{cases} \qquad (1)$$

The membership functions of the linguistic values of the weights of criteria are shown in Figure 1, and the triangular fuzzy numbers related to these variables are presented in Table 1.

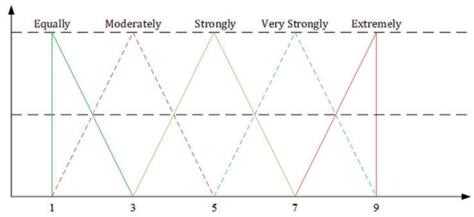

Figure 1. *Linguistic Values of the Weights of Criteria*

$$M_{g_i}^1, M_{g_i}^2, \cdots, M_{g_i}^m \quad i=1,2, ..., n \tag{3}$$

Chang's extent analysis [24] follows the steps described below respectively [26, 27, 28]:

Step 1: The fuzzy synthetic extent value with respect to the i_{th} object is defined as

$$S_i = \sum_{j=1}^{m} M_{gi}^j \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1} \tag{4}$$

$\sum_{j=1}^{m} M_{g_i}^j$ is calculated by fuzzy addition operation of m extent analysis values for a particular matrix as given below:

$$\sum_{i=1}^{m} M_{g_i}^j = \left(\sum_{i=1}^{m} l_i, \sum_{i=1}^{m} m_i, \sum_{i=1}^{m} u_i\right) \tag{5}$$

and to obtain $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^j\right]^{-1}$, the Eq. (6) and Eq. (7) are implemented respectively:

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^j = \left(\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i\right) \tag{6}$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^j\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \tag{7}$$

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 defined as:

Table 1. *Linguistic Values and TFNs to Evaluate the Weights of Criteria*

Linguistic variables	Triangular fuzzy numbers	Triangular reciprocal fuzzy numbers
Just equal (JE)	(1, 1, 1)	(1, 1, 1)
Equal importance (EI)	(1, 1, 3)	(1/3, 1, 1)
Weak importance (WI)	(1, 3, 5)	(1/5, 1/3, 1)
Strong importance (SI)	(3, 5, 7)	(1/7, 1/5, 1/3)
Very strong importance (VSI)	(5, 7, 9)	(1/9, 1/7, 1/5)
Extremely preferred (EP)	(7, 9, 9)	(1/9, 1/9, 1/7)

By using linguistic variables and related TFNs in Table 1, the fuzzy judgement matrix $\tilde{A}(\tilde{a}_{ij})$, obtained via pairwise comparisons, can be expressed as follows:

$$\tilde{A} = \begin{bmatrix} (1,1,1) & \begin{matrix}\tilde{a}_{121}\\ \tilde{a}_{122}\\ \vdots\\ \tilde{a}_{12P_{12}}\end{matrix} & \cdots & \begin{matrix}\tilde{a}_{1n1}\\ \tilde{a}_{1n2}\\ \vdots\\ \tilde{a}_{1nP_{1n}}\end{matrix} \\ \begin{matrix}\tilde{a}_{211}\\ \tilde{a}_{212}\\ \vdots\\ \tilde{a}_{21P_{21}}\end{matrix} & (1,1,1) & \cdots & \begin{matrix}\tilde{a}_{2n1}\\ \tilde{a}_{2n2}\\ \vdots\\ \tilde{a}_{2nP_{2n}}\end{matrix} \\ \vdots & \vdots & \ddots & \vdots \\ \begin{matrix}\tilde{a}_{n11}\\ \tilde{a}_{n12}\\ \vdots\\ \tilde{a}_{n1P_{n1}}\end{matrix} & \begin{matrix}\tilde{a}_{n21}\\ \tilde{a}_{n22}\\ \vdots\\ \tilde{a}_{n2P_{n2}}\end{matrix} & \cdots & (1,1,1) \end{bmatrix} \tag{2}$$

Let $X = \{x_1, x_2, \cdots, x_n\}$ be an object set and $G = \{g_1, g_2, \cdots, g_n\}$ is a goal set. According to Chang's fuzzy extent analysis, each object, x_i, is taken and extent analysis is performed for each goal, g_i. Therefore, m extent analysis for each object can be obtained, given as:

$$V(M_2 \geq M_1) = \sup_{y \geq x}[\min(\mu_{M_1}(x), \mu_{M_2}(y),)] \quad (8)$$

and Eq. (8) can be defined as follows:

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \mu_{M_2}(d) \quad (9)$$

$$\mu_{M_2}(d) = \begin{cases} 1, & if\ m_2 \geq m_1 \\ 0, & if\ l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & \text{otherwise} \end{cases} \quad (10)$$

where, as seen in Figure 2, *d* represents the ordinate of the highest intersection point *D* between μ_{M1} and μ_{M2}. We need to calculate the values of $V(M_1 \geq M_2)$ and $V(M_1 \geq M_2)$ to make a comparison of M_1 and M_2.

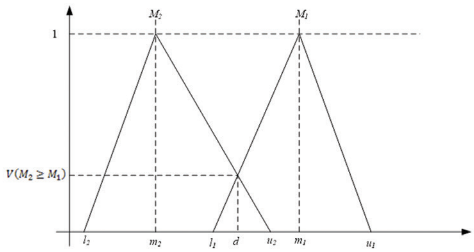

Figure 2. *The Intersection Between M_1 and M_2*

Step 3: The possibility degree of a convex fuzzy number to be greater than k convex fuzzy numbers M_i *(i = 1,2,3, ..., k)* can be defined by

$$V(M \geq M_1, M_2, \cdots, M_k) = V[(M \geq M_1)\ and\ (M \geq M_2)\ and \ldots and\ (M \geq M_k)] = \min V(M \geq M_i) \quad (11)$$

Assuming that $d'(A_i) = \min V(S_i \geq S_k)$ for $k = 1,2, ... n; k \neq i$ Then, the weight vector is given by as:

$$W' = (d'(A_1), d'(A_2), \cdots, d'(A_k))^T \quad (12)$$

where A_i (1,2,⋯,n) has n elements.

Step 4: With normalization, the normalized weight vectors are given as:

$$W = (d(A_1), d(A_2), \cdots, d(A_k))^T \quad (13)$$

where W is a non-fuzzy number.

3.2. Fuzzy TOPSIS (F-TOPSIS)

TOPSIS is a MCDM method which was developed by Hwang and Yoon [23] in 1981. It provides to select the best alternative based on the ranking the alternatives under multiple criteria. In the study, to handle the ambiguities, uncertainties, and vagueness in the selection problem, TOPSIS method with fuzzy logic is used. It is possible to find many applications of F-TOPSIS in the literature. The extended version of TOPSIS with fuzzy logic proposed by Chen [29] is preferred to use in the study. The corresponding steps of this method are described as follows;

Step 1: The weights of the criteria (*w; j = 1, 2, ... , number of criteria*) and performance ratings of alternatives under each criterion (x_{ij}; *i = 1, 2, ... , m, number of alternatives, j = 1, 2, ... , number of criteria*) are accepted as inputs and placed in matrix form. The performance ratings, X_{ij}, of alternatives are assigned by the expert with the help of linguistic variables presented in Table 2.

Table 2. *Linguistic Variables for Ratings*

Linguistic variable	Triangular fuzzy number
Very Low	(1, 1, 3)
Low	(1, 3, 5)
Medium	(3, 5, 7)
High	(5, 7, 9)
Very High	(7, 9, 9)

With the assignments of the expert for each alternative under each criterion, the decision matrix is constructed as follows:

	C_1	C_2	⋯	C_j	⋯	C_n
A_1	$\tilde{x}_{11}$	$\tilde{x}_{12}$	⋯	$\tilde{x}_{1j}$	⋯	$\tilde{x}_{1n}$
A_2	$\tilde{x}_{21}$	$\tilde{x}_{22}$	⋯	$\tilde{x}_{2j}$	⋯	$\tilde{x}_{2n}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮
A_m	$\tilde{x}_{m1}$	$\tilde{x}_{m2}$	⋯	$\tilde{x}_{mj}$	⋯	$\tilde{x}_{mn}$

Step 2: Following with the construction of the decision matrix, the normalization of the decision matrix is performed using Eq. (14) and Eq. (15):

$$\tilde{v}_{ij} = \left(\frac{a_{ij}}{c_i^*}, \frac{b_{ij}}{c_i^*}, \frac{c_{ij}}{c_i^*}\right), \quad i \in Benefit \quad (14)$$

$$\tilde{v}_{ij} = \left(\frac{a_i^-}{c_{ij}}, \frac{a_i^-}{b_{ij}}, \frac{a_i^-}{a_{ij}}\right), \quad i \in Cost \quad (15)$$

and c_i^* and a_i^- is calculated using Eq. (16) and Eq. (17);

$$c_i^* = \max_j c_{ij}, \quad if \;\; i \in Benefit \quad (16)$$

$$a_i^- = \min_j a_{ij}, \quad if \; i \in Cost \quad (17)$$

Step 3: The weighted normalized decision matrix is found by multiplying the weights of selection criteria with normalized decision matrix elements.

$$\tilde{V} = [\tilde{v}_{ij}]_{m \times n} \quad i = 1, 2, \cdots, m \; j = 1, 2, \cdots, n \quad (18)$$

where

$$\tilde{v}_{ij} = \widetilde{x_{ij}} \times w_i \quad (19)$$

Step 4: Fuzzy Positive Ideal Solution (FPIS) and the Fuzzy Negative Ideal Solution (FNIS) for each criterion are taken $\tilde{v}_i^+ = (1,1,1)$ ve $\tilde{v}_i^- = (0,0,0)$ respectively.

$$A^+ = \{\tilde{v}_1^+, \cdots, \tilde{v}_j^+, \cdots, \tilde{v}_m^+\} \quad (20)$$

$$A^- = \{\tilde{v}_1^-, \cdots, \tilde{v}_j^-, \cdots, \tilde{v}_m^-\} \quad (21)$$

Step 5: Then, the distance of each alternative from (A^+) and (A^-) are calculated as:

$$D_j^+ = \sum_{i=1}^{m} d\left(\tilde{v}_{ij}, \tilde{v}_i^+\right), \quad j = 1,2,\cdots,n \quad (22)$$

$$D_j^- = \sum_{i=1}^{m} d\left(\tilde{v}_{ij}, \tilde{v}_i^-\right), \quad j = 1,2,\cdots,n \quad (23)$$

According to the vertex method, the distance between the TFNs is calculated with the help of Eq. (24).

$$d(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}[(l_1 - l_2)^2 + (m_1 - m_2)^2 + (u_1 - u_2)^2]} \quad (24)$$

Step 6: As a final step, closeness coefficient (CC_j) is calculated to rank all possible alternatives.

$$CC_j = \frac{D_j^-}{D_j^+ + D_j^-} \quad , j = 1,2,\cdots,n \quad (25)$$

The alternative with the maximum CC_j can be selected as a most preferred option.

4. An Application: Shipboard Wastewater Treatment System Selection

The knowledge-based expert system on SWWTS selection consists of three basic stages: (1) determination the criteria and appropriate SWWTS alternatives, (2) calculation the weights of the criteria with F-AHP, (3) evaluation of alternatives with F-TOPSIS. The framework of the proposed system is presented in Figure 3. The selection criteria, alternative SWWTSs and numerical outcomes of the application are presented in the subsections respectively.

4.1. Definition of Selection Criteria

The Selection Criteria (SC) are determined with the help of literature review and industrial feedbacks. With the lack of the SWWTS selection studies in the literature, the studies such as; Buyukozkan et al. [6], Zeng et al. [8], Bottero et al. [12], Karimi et al. [13], Kalbar et al. [14], Ilangkumaran [15] and Upadhyay [16] were comprehensively analysed to figure out the general intensity on the identification the selection criteria and determination the weight of each one. Additionally, to adopt ship specific constraints into determination of the SC, the industrial feedbacks such as international standard [30], IMO circular [31], technical reports [32, 33] and news releases [34] and the manufacturers' publications [35, 36] were reviewed. Within this direction, SC of the SWWTS problem was determined as operability & maintainability (SC_1), space requirement (SC_2), energy consumption (SC_3), capital cost (SC_4), operation and maintenance cost (SC_5), and environmental compatibility (SC_6).

The SC_1 criterion considerably affects the useful life of the system. Hence it is essential to take into consideration in the

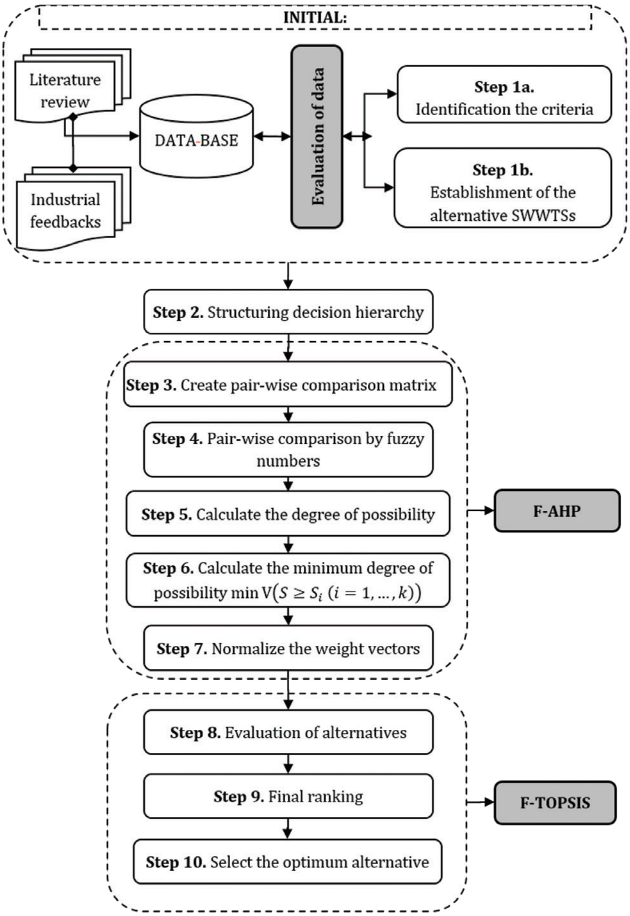

Figure 3. *Knowledge-Based Expert System on SWWTS Selection*

selection process. The SC_2 criterion focuses on the volume and weight of the system. With the limited engine room space on board ship, the volume and weight of the SWWTS turn into an important criterion on the selection process. The international enforcement related to the energy efficiency on board ships, the energy consumptions of the systems becomes quite an essential issue nowadays. For this reason, SC_3 criterion is accepted as another essential selection criterion in the study. The capital cost of the system has always a priority and substantially influences the selection of the system. At this insight, the SC_4 criterion is used in the selection of the system. In addition to capital cost, operation and maintenance cost plays a significant role in the determination of the most suitable system. To provide the system in reliable condition, it is necessary to endure the operation and maintenance cost throughout the useful life of the system. Hence SC_5 criterion is considered as an important selection criterion. Another important criterion in the selection of SWWTS is environmental compatibility. This criterion focuses on ensuring environmental regulations, meeting tough effluent discharge requirements, treating both black and grey water, no dangerous chemical additives and no microorganism to maintain for SWWTS.

The selection of optimum SWWTS which mostly fulfil the expectations is conducted under the aforementioned selection criteria. The alternatives SWWTSs, which are mostly preferred types on board ships, are presented in the following subsection.

4.3. Alternative SWWTSs

The proposed SWWTS selection procedure is demonstrated with three most commonly used alternatives on board ship which are biological, chemical and membrane wastewater treatment system. The general treatment principles of selected alternative SWWTSs are briefly explained in the following paragraphs.

Biological SWWTS (A_1) uses bacteria to facilitate the process of breaking down of solid constituents. The system consists of three compartments namely; (i) aeration compartment, (ii) settling compartment, and (iii) chemical treatment compartment. In the aeration compartment, an oxygen-rich atmosphere is generated to disintegrate the sewage waste. The disintegrated waste is then transferred to the settling compartment to settle down the solid constituents with the effect of gravity. The separated liquid from solid constituents is passed to the chemical treatment compartment. In this compartment, the liquid water is treated with chemicals to kill any surviving bacteria. After treatment, the treated water is discharged into the sea and the sludge of the wastewater is stored in a tank.

Chemical SWWTS (A_2) consists of a big storage tank which collects, treats and stores the wastewater on board ship. The collected wastewater in the storage tank is treated by chemicals to disintegrate solid constituents in the water. Also, in the chemical SWWTS, a mechanical instrument, with the name of comminutor, is used to break down the solid particles to smaller particles. The disintegrated solid particles settle down in the tank and the liquid remains at the top. Then the liquid sewage is treated with chemicals. The treated liquid can be as a flushing purpose in the toilet and can be discharged to the sea.

In the membrane SWWTS (A_3), wastewater passes into Membrane Bioreactor (MBR) which consists of a combination of membrane and biological reactor [37, 38]. In the MBR, biological purification of the sewage water occurs with the help of activated sludge which is a mixture of a number of micro-organisms [38]. Then, the treated water is separated from the activated sludge by means of filtration. Finally, the treated water is discharged into the sea and the sludge of wastewater is transferred into the tank on board.

4.4. Numerical Outcomes

With the determination of selection criteria and SWWTS alternatives, decision hierarchy is established accordingly and it is provided in Figure 4.

Following the establishment of the decision hierarchy, the weights of the criteria to be used in the selection process are calculated with the help of F-AHP method. In this phase, the expert, from one of the leading global manufacturers of equipment for ships, with six years on board and nine years onshore experiences in the maritime industry joined the selection process of the suitable SWWTS. Then, the

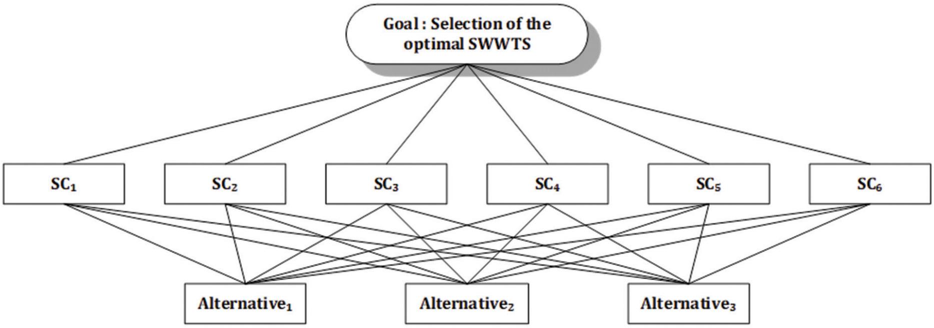

Figure 4. *The Decision Hierarchy of WWTP Selection*

Table 3. *The Sample Part of the Questionnaire*

SC_1	*EP*	*VSI*	*SI*	*WI*	*EI*	*JE*	*EI*	***WI***	*SI*	*VSI*	*EP*	**SC_2**
SC_1	*EP*	*VSI*	*SI*	*WI*	***EI***	*JE*	*EI*	*WI*	*SI*	*VSI*	*EP*	**SC_3**
SC_1	*EP*	*VSI*	*SI*	*WI*	*EI*	*JE*	*EI*	*WI*	***SI***	*VSI*	*EP*	**SC_4**
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
SC_5	*EP*	*VSI*	*SI*	*WI*	*EI*	*JE*	*EI*	***WI***	*SI*	*VSI*	*EP*	**SC_6**

Table 4. *The Pairwise Comparison Matrix for Criteria*

	SC_1	**SC_2**	**SC_3**	**SC_4**	**SC_5**	**SC_6**
SC_1	(1.00, 1.00, 1.00)	(0.20, 0.33, 1.00)	(1.00, 1.00, 3.00)	(0.14, 0.20, 0.33)	(0.20, 0.33, 1.00)	(0.11, 0.14, 0.20)
SC_2	(1.00, 3.00, 5.00)	(1.00, 1.00, 1.00)	(1.00, 3.00, 5.00)	(0.33, 1.00, 1.00)	(1.00, 3.00, 5.00)	(0.14, 0.20, 0.33)
SC_3	(0.33, 1.00, 1.00)	(0.20, 0.33, 1.00)	(1.00, 1.00, 1.00)	(0.20, 0.33, 1.00)	(0.20, 0.33, 1.00)	(0.14, 0.20, 0.33)
SC_4	(3.00, 5.00, 7.00)	(1.00, 1.00, 3.00)	(1.00, 3.00, 5.00)	(1.00, 1.00, 1.00)	(1.00, 3.00, 5.00)	(0.33, 1.00, 1.00)
SC_5	(1.00, 3.00, 5.00)	(0.20, 0.33, 1.00)	(1.00, 3.00, 5.00)	(0.20, 0.33, 1.00)	(1.00, 1.00, 1.00)	(0.20, 0.33, 1.00)
SC_6	(5.00, 7.00, 9.00)	(3.00, 5.00, 7.00)	(3.00, 5.00, 7.00)	(1.00, 1.00, 3.00)	(1.00, 3.00, 5.00)	(1.00, 1.00, 1.00)

expert is given the task to make pairwise comparisons of the selection criteria by using the scale given in Table 1 through the structured questionnaire, sample part illustrated in Table 3.

Then, linguistic pairwise comparisons of the expert are converted into fuzzy numbers and obtained pairwise comparison matrix is illustrated in Table 4.

Being able to be understood more clearly of the computation stages, the following calculation of the pairwise judgments in Table 4 are presented. The following calculations are implemented with the help of Eq. (4), Eq. (5), Eq. (6) and Eq. (7).

$$S_{SC_1} = (2.65, 3.01, 6.53) \otimes \left(\frac{1}{97.20}, \frac{1}{61.41}, \frac{1}{34.14}\right) = (0.027, 0.049, 0.191)$$

$$S_{SC_2} = (4.48, 11.20, 17.33) \otimes \left(\frac{1}{97.20}, \frac{1}{61.41}, \frac{1}{34.14}\right) = (0.046, 0.182, 0.508)$$

$$S_{SC_3} = (2.08, 3.20, 5.33) \otimes \left(\frac{1}{97.20}, \frac{1}{61.41}, \frac{1}{34.14}\right) = (0.021, 0.052, 0.156)$$

$$S_{SC_4} = (7.33, 14.00, 22.00) \otimes \left(\frac{1}{97.20}, \frac{1}{61.41}, \frac{1}{34.14}\right) = (0.075, 0.228, 0.644)$$

$$S_{SC_5} = (3.60, 8.00, 14.00) \otimes \left(\frac{1}{97.20}, \frac{1}{61.41}, \frac{1}{34.14}\right) = (0.037, 0.130, 0.410)$$

$$S_{SC_6} = (14.00, 22.00, 32.00) \otimes \left(\frac{1}{97.20}, \frac{1}{61.41}, \frac{1}{34.14}\right) = (0.144, 0.358, 0.937)$$

The obtained fuzzy synthetic extent value (S_{SCi} $i = 1,2,\ldots,6$) of each selection criterion is used to calculate the possibility degrees with using Eq. (8), Eq. (9) and Eq. (10) and illustrated below.

$$V(S_{SC_1} \geq S_{SC_2}, S_{SC_3}, S_{SC_4}, S_{SC_5}, S_{SC_6}) = 0.170$$

$$V(S_{SC_2} \geq S_{SC_1}, S_{SC_3}, S_{SC_4}, S_{SC_5}, S_{SC_6}) = 0.673$$

$$V(S_{SC_3} \geq S_{SC_1}, S_{SC_2}, S_{SC_4}, S_{SC_5}, S_{SC_6}) = 0.038$$

$$V(S_{SC_4} \geq S_{SC_1}, S_{SC_2}, S_{SC_3}, S_{SC_5}, S_{SC_6}) = 0.793$$

$$V(S_{SC_5} \geq S_{SC_1} S_{SC_2}, S_{SC_3}, S_{SC_4}, S_{SC_6}) = 0.539$$

$$V(S_{SC_6} \geq S_{SC_1}, S_{SC_2}, S_{SC_3}, S_{SC_4}, S_{SC_5}) = 1$$

Following with the calculation of possibility degrees, the weight vector is calculated as using Eq. (12) and Eq. (13):

$$W' = (0.170, 0.673, 0.038, 0.793, 0.539, 1)^T$$

With normalization, the weights of the criteria are calculated as follows:

$$W = \left(d(SC_1), d(SC_2), d(SC_3), d(SC_4), d(SC_5), d(SC_6)\right)^T$$

$$W = (0.053, 0.210, 0.012, 0.247, 0.168, 0.311)^T$$

The SC_6 is obtained as a most important criterion respect to the pairwise comparisons of the expert. Additionally, SC_4 and SC_2 are determined as the second and third most important criterion respectively for the selection process of SWWTS.

After calculation of the weights, *as the first step of F-TOPSIS method*, the decision matrix based on the expert judgements by comparing alternatives with the help of linguistic variables presented in Table 2, is established. The obtained decision matrix is presented in Table 5.

Table 5. *Decision Matrix on SWWTS Selection*

Criterion / ***Alternative***	SC_1 *(0.053)*	SC_2 *(0.210)*	SC_3 *(0.012)*	SC_4 *(0.247)*	SC_5 *(0.168)*	SC_6 *(0.311)*
A_1	Medium (3, 5, 7)	Low (1, 3, 5)	Medium (3, 5, 7)	High (5, 7, 9)	Medium (3, 5, 7)	High (5, 7, 9)
A_2	High (5, 7, 9)	Medium (3, 5, 7)	Low (1, 3, 5)	Medium (3, 5, 7)	High (5, 7, 9)	Low (1, 3, 5)
A_3	Medium (3, 5, 7)	Low (1, 3, 5)	High (5, 7, 9)	Very High (7, 9, 9)	Medium (3, 5, 7)	Very High (7, 9, 9)

Following with the determination of the decision matrix, the normalized decision matrix with using the Eq. (14) for benefit criterion and Eq. (15) for cost criterion is derived. In the selection problem, SC_1, SC_2 and SC_6 are benefit criteria and SC_3, SC_4, and SC_5 are cost criteria. Then, the weighted normalized decision matrix is calculated with the help of Eq. (19) using the weights of the criteria. The weighted normalized decision matrix is shown in Table 6.

Table 6. Weighted Decision Matrix on SWWTS Selection

	SC1	SC2	SC3	SC4	SC5	SC6
A1	(0.018, 0.029, 0.041)	(0.030, 0.090, 0.150)	(0.002, 0.002, 0.004)	(0.082, 0.106, 0.148)	(0.072, 0.101, 0.168)	(0.173, 0.242, 0.311)
A2	(0.029, 0.041, 0.053)	(0.090, 0.150, 0.210)	(0.002, 0.004, 0.012)	(0.106, 0.148, 0.247)	(0.056, 0.072, 0.101)	(0.035, 0.104, 0.173)
A3	(0.018, 0.029, 0.041)	(0.030, 0.090, 0.150)	(0.001, 0.002, 0.002)	(0.082, 0.106, 0.106)	(0.072, 0.101, 0.168)	(0.242, 0.311, 0.311)
A^+	$\widetilde{v_1^+}$ = (1.0, 1.0, 1.0)	$\widetilde{v_2^+}$ = (1.0, 1.0, 1.0)	$\widetilde{v_3^+}$ = (1.0, 1.0, 1.0)	$\widetilde{v_4^+}$ = (1.0, 1.0, 1.0)	$\widetilde{v_5^+}$ = (1.0, 1.0, 1.0)	$\widetilde{v_6^+}$ = (1.0, 1.0, 1.0)
A^-	$\widetilde{v_1^-}$ = (0.0,0.0, 0.0)	$\widetilde{v_2^-}$ = (0.0, 0.0, 0.0)	$\widetilde{v_3^-}$ = (0.0, 0.0, 0.0)	$\widetilde{v_4^-}$ = (0.0, 0.0, 0.0)	$\widetilde{v_5^-}$ = (0.0, 0.0, 0.0)	$\widetilde{v_6^-}$ = (0.0, 0.0, 0.0)

After calculation of weighted normalized decision matrix, FPIS (A^+) and FNIS (A^-) are defined as $\widetilde{v_i^+}$ = (1.0, 1.0, 1.0) and $\widetilde{v_i^-}$ = (0.0,0.0, 0.0) for all criterion.

The distance from A^+ (F-PIS), D_i^+, and A^- (F-NIS), D_i^-, for each alternative is calculated using Eq. (22) and Eq. (23). With the calculated distances from F-PIS and F-NIS, the CC_j of each alternative is calculated with the help of Eq. (25). The results of F-TOPSIS are summarized in Table 6.

Table 6. F-TOPSIS Results

Alternatives	D_j^+	D_j^-	CC_j	Rank
A1	5,416	0,620	0,735	2
A2	5,462	0,581	0,687	3
A3	5,406	0,621	0,736	1

Based on CC_j values, A_3, *membrane SWWTS*, is found as a best alternative with CC value of 0.736. On the other hand, as seen from Table 6, CC values of A_1, *Biological SWWTS*, and A_3, *membrane SWWTS*, are quite close to each other. For this reason, A_1 can be considered as another preferable solution.

4.5. Finding and Discussions

The study evaluates a number of key criteria on SWWTS selection. As the beginning of the analysis, the weights of the criteria are obtained as W_{SC1}=0.053, W_{SC2}=0.210, W_{SC3}=0.012, W_{SC4}=0.247, W_{SC5}=0.168, W_{SC6}=0.311. It is clearly seen from the results that SC_6 is found as the most important criterion in the selection of SWWTSs. Also, according to the results obtained from F-AHP, SC_4 criterion is the second, SC_2 criterion is the third, SC_5 criterion is the fourth, SC_1 criterion is the fifth and SC_3 criterion is the least important criterion.

Subsequent to the calculation of the weights, F-TOPSIS method is implemented to evaluate the alternative SWWTSs. The results obtained from F-TOPSIS method show that, although chemical SWWTS is better than the other alternatives with respect to the criteria of operability and maintainability, energy consumption and capital cost shortcoming in environmental compatibility made chemical SWWTS the last preference. On the other hand, membrane SWWTS is found as a best (optimum) SWWTS with its advantages in space requirement and environmental compatibility. Additionally, with technical advances, membrane SWWTS is now capable of decontaminating wastewaters in single step processes.

Avowable, the proposed knowledge-based expert system with its outstanding results helps decision makers to take the right decision on selection of the optimum ship wastewater treatment system.

5. Conclusion

SWWTS selection is an onerous process of maritime environmental management. The developing technology enables various options and selection of SWWTSs which are dependent on many factors. This study explored the potential SWWTS alternatives in the shipping industry and proposed an integrated fuzzy MCDM framework for effective SWWTS selection. The proposed methodology integrates the F-AHP and F-TOPSIS methods. The methodology provides stakeholders, ship owners, marine engineers, ship designers, and manufacturers, with a flexible manner to experience the present situation of SWWTSs and to deal with the selection of SWWTSs in the practical environmental management application. The proposed methodology enables flexibility and increases the reliability and accuracy of applications. For this reason, the proposed methodology can be extended for various environmental management applications such as the selection of alternative technologies for decreasing NO_X emission on board ship and selection of oily water treatment technologies as further studies. In addition, this study can also be extended by implementing Analytic Network Process (ANP) method whose network structure caters to all possible dependencies and interactions among selection criteria.

References

[1] North Atlantic Treaty Organization (NATO), (2010). Maritime Environmental Protection -Strategy for enhancing naval operations through ship and equipment design and management practices. (Website of NATO: www.nato.int)

[2] Balmer, P., & Mattson, B. (1994). Wastewater treatment plant operation cost. Water Science and Technology, 30 (4), 7–15.

[3] Sarkis, J., and Weinrach, J. (2001). Using data envelopment analysis to evaluate environmentally conscious waste treatment technology. Journal of Cleaner Production, 9(5), Pages 417-427.

[4] Tsagarakis, K.P., Mara, D.D., & Angelakis, A.N. (2003). Application of Cost Criteria for Selection of Municipal Wastewater Treatment Systems. Water, Air, & Soil Pollution, 142(1-4), 187-210.

[5] Büyüközkan, G., Feyzioglu, O., & Sever, F. (2005). An application of multi criteria decision making approaches for the wastewater treatment system selection problem. 35th International Conference on Computers and Industrial Engineering, 19-22 June, Istanbul, Turkey, 345-350.

[6] Sato, N., Okubo, T., Onodera, T., Agrawal, L.K., Ohashi, A., & Harada, H. (2007). Economic evaluation of sewage treatment processes in India. Journal of Environmental Management, 84(4),447-460.

[7] Anagnostopoulos, K.P, Gratziou, M., & Vavatsikos, A.P. (2007) Using the fuzzy Analytic Hierarchy Process for selecting wastewater facilities at prefecture level. European Water, 19(20), 15-24.

[8] Zeng, G., Jiang, R., Huang, G., Xu, M., & Lia, J. (2007). Optimization of wastewater treatment alternative selection by hierarchy grey relational analysis. Journal of Environmental Management, 82(2), 250-259.

[9] Alsina, X.F., Roda, I.R., Sin, G., & Gernaey, K.V. (2008). Multi-criteria evaluation of wastewater treatment plant control strategies under uncertainty. Water Research, 42(17), 4485-4497.

[10] De Foe G., De Gisi, S., & Galasso, M. (2008). Definition of a practical multi-criteria procedure for selecting the best coagulant in a chemically assisted primary sedimentation process for the treatment of urban wastewater. Desalination, 230(1-3), 229-238.

[11] Alsina X.F., Gallego, A., Feijoo, G., & Roda, I.R. (2010). Multiple-objective evaluation of wastewater treatment plant control alternatives. Journal of Environmental Management, 91(5), 1193-1201.

[12] Bottero, M., Comino, E., & Riggio, V. (2011). Application of the analytic hierarchy process and the analytic network process for the assessment of different wastewater treatment systems. Environmental Modelling & Software, 26(10), 1211-1224.

[13] Karimi, A. R., Mehrdadi, N., Hashemian, S. J., Bidhendi, G. R. N., & Moghaddam, R. T. (2011). Selection of wastewater treatment process based on the analytical hierarchy process and fuzzy analytical hierarchy process methods. International Journal of Environmental Science & Technology, 8(2), 267–280.

[14] Kalbar, P. P., Karmakar, S., & Asolekar, S. R. (2012). Selection of an appropriate wastewater treatment technology: A scenario-based multiple-attribute decision-making approach. Journal of environmental management, 113, 158-169.

[15] Ilangkumaran, M., Sasirekha, V., Anojkumar, L., Sakthivel, G., Boopathi Raja, M., T. Ruban Sundara Raj, CNS. Siddhartha, P. Nizamuddin and S. Praveen Kumar (2013). Optimization of wastewater treatment technology selection using hybrid MCDM. Management of Environmental Quality: An International Journal, 24(5), 619–641.

[16] Upadhyay, K. (2017). Application of Analytical Hierarchy Process in Evaluation of Best Sewage Treatment Plant. International Journal of Science and Research, 6(6), 259-264.

[17] Demboski D.J., Benson J.H., Rossi G.E., Leavitt N.S., Mull M.A. (1997). Evolutions in U.S. Navy Shipboard Sewage and Greywater Programs. American Society of Naval Engineers (ASNE) Environmental Symposium '97.

[18] Eley, W.D., & Morehouse, C.H. (2003). Evaluation of new technology for shipboard wastewater treatment. Proceedings of Oceans 2003 Conference, Marine Technology Society, Columbia, Maryland, 748-753.

[19] International Council of Marine Industry Association (ICOMIA), (2007). ICOMIA guide to on-board treatment of grey-water, 2nd-Edition.

[20] Torfi F., Farahani, R.Z., & Rezapour, S. (2010). Fuzzy AHP to determine the relative weights of evaluation criteria and Fuzzy TOPSIS to rank the alternatives. Applied Soft Computing, 10, 520-528.

[21] Saaty, T.L. (1980). The Analytic Hierarchy Process. McGraw Hill Company, New York.

[22] Saaty, T.L. (1988). Multi-criteria Decision Making: The Analytic Hierarchy Process, RWS Publications, Pittsburgh, PA.

[23] Hwang, C.L., & Yoon, K., (1981). Multiple Attributes Decision Making Methods and Applications, Springer, Berlin Heidelberg.

[24] Chang, D.Y. (1992). Extent analysis and synthetic decision. Optimization Techniques and Applications, 1, 352–355.

[25] Triantaphyllou, E. (2000) Multi-Criteria Decision Making Methods: A Comparative Study. Kluver Academic Publishers, Dordrecht.

[26] Bozbura, F. T., Beşkese, A., & Kahraman, C. (2007). Prioritization of human capital measurement indicators using fuzzy AHP. Expert Systems with Applications, 32, 1100–1112.

[27] Kahraman, C., Cebeci, U., & Ruan, D. (2004). Multi-attribute comparison of catering service companies using fuzzy AHP: The case of Turkey. International Journal of Production Economics, 87, 171–184.

[28] Kahraman, C., Ruan, D., & Doğan, I. (2003). Fuzzy group decision making for facility location selection. Information Sciences, 157, 135–153.

[29] Chen, C.T. (2000) Extensions of the TOPSIS for group decision making under fuzzy environment. Fuzzy Sets and Systems, 114, pp.1-9.

[30] International Standard Organization, (2004). ISO 15749-1:2004: Ships and marine technology - Drainage systems on ships and marine structures - Part 1: Sanitary drainage-system design.

[31] International Maritime Organization Publication (1994). MSC/Circ. 648, Annex Guidelines for the operation, inspection and maintenance of ship sewage systems.

[32] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/282353/mgn033.pdf

[33] Web Page: www.emsa.europa.eu/work/download/4557/2925/23.html

[34] Web Page: https://www.ship-technology.com/contractors/wastewater/techni-sa/

[35] WebPage:http://www.headhunterinc.com/product/sewage-treatment-2/?gclid=EAIaIQobChMIxJm-zqTo3wIVk0PTCh0rqg1_EAMYAyAAEgIvVfD_BwE

[36] Web Page: http://hosent.co.kr/

[37] Visvanathan, Chettiyappan & Ben Aim, Roger. (2018). Membrane Bioreactor Applications in Wastewater Treatment.

[38] Web Page: http://www.acomarine.com/products/wastewater-treatment-plants/membrane-wastewater-treatment-system/, 06.12.2018, 14:11.