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A quantitative approach to the development of ballast water treatment systems in ships

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ABSTRACT
Selection of the right ship ballast water treatment system is quite costly. In the present study, a decision-making approach was developed based on the associated issues, processes and the best solution under current conditions for selecting the ballast water treatment system for ships. The analysis of the study data revealed that the best decision-making system should include integrated DEMATEL (The Decision Making Trial and Evaluation Laboratory) and ANP (Analytic Network Process) methods, especially since the current criteria interacted, there was a network among the criteria sets, and the system approach should be holistic. The study findings demonstrated that C4 (impact on the technical status of the ship) was the most significant criterion, while C11 (initial investment cost) was the most significant sub-criterion.

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KEYWORDS
Ship investment decisions; ballast water treatment system; demetel; ANP

1. Introduction

Maritime transportation is the most preferred global mode of transport. Ships, cargoes and ports are the main elements of maritime transport. About 90% of the total global cargo is transported by ships (Cheaitou and Cariou 2018; Fang et al. 2020). This high rate is natural since the maritime vessels play a key role in fulfilling human needs timely, helping maintain global trade without interruption and sustaining supply chain integration (Mansouri et al. 2015; Wong et al. 2015; Zaman et al. 2015; Dui et al. 2021).

Certain regulations and standards are required for safe and sustainable maritime traffic. (Zhou et al. 2020; Dui et al. 2021). Thus, the International Maritime Organization (IMO) issues global maritime regulations, ensures the implementation of these regulations, and is responsible for the systematic and safe maintenance of maritime transport. IMO has enacted several international conventions, agreements and practices since its establishment. Technological advances and novel requirements have led to new practices. One of these is the 'International Convention for the Control and Management of Ships' Ballast Water and Sediments' (IMO 2004, 2014, 2018). The main goals of the convention are to prevent the potential health, environmental and economic problems that could be caused by harmful species transported in ships' ballast on target ecosystems (IMO 2004, 2014, 2018; MEPC 2016). It was estimated that around 10 billion tons of ballast water are globally transported in ships annually, and approximately 10,000 living species are discharged into various marine ecosystems per day through the ballast water. These species could biologically invade marine regions, leading to serious problems for national economies, human health and the environment (IMO 2007; Briski et al. 2015; Seebens et al. 2016; David and Gollasch 2019; Saebi et al. 2020; Wang et al. 2021).

Although the convention entered into force on September 8, 2017, meeting the convention's requirements was not possible until 2021, and it was reported that even as of 2022, most ships are yet to adapt to the system (Doğru et al. 2021; Sayinli et al. 2022). The most important reasons for the delay included the complexity of the problem that entailed various fields, difficulties in the development of the guides and technology to determine the ballast water discharge standards specified in the convention (Campara et al. 2019; Lv et al. 2020). Furthermore, the uncertainties in state control of the ports, ballast water sampling and analysis facilities played a significant role in this delay. Due to these problems, the installation of the treatment system in certain ships (International Convention for the Control and Management of Ships' Ballast Waters and Sediments – D2 Standards) has been gradually delayed to September 8, 2024, based on the IOPP (International Oil Pollution Prevention) certificate renewal dates (Cheng et al. 2019; Doğru et al. 2021; Lakshmi et al. 2021).

Several ballast water treatment methods have been developed to ensure the installation of the ballast water treatment mechanism on ships based on the IMO standards (Vorkapić et al. 2016; Darling et al. 2018; Hess-Erga et al. 2019). These methods are categorised into three groups: mechanical, physical and chemical processes (Olsen et al. 2015; Darling et al. 2018). However, any one of these methods is not sufficient for treating ship ballast water, and mixed techniques that integrate the above-mentioned methods were developed (Vorkapić et al. 2016). The treatment entails the capture of the existing particles and large organisms in the ship ballast water by mechanical methods. Then, when there are active substances in the ship's ballast water, the disinfectant by-products and residues in the effluent are neutralised (Cheng et al. 2019). Special filters and chemicals called hydro-cyclones are used in this process (Campara et al. 2019; Lv et al. 2020). However, one of the most preferred physical methods is ultra-violet (UV) purification (Briski et al. 2015; Lundgreen et al. 2019; Lakshmi et al. 2021). Also, other physical methods, such as deoxygenation, cavitation and heat treatment, are employed. Various chemicals could also be used directly, and the disinfectant could be produced on the ship with seawater electrolysis (Makkonen and Inkinen 2021; Wang et al. 2021). Each method has advantages and disadvantages (Gerhard et al. 2019). Over a hundred approved systems that meet IMO standards are available (Doğru et al. 2021). The review of these systems would demonstrate that the filtration technique is

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the most preferred pre-treatment method (Wang and Corbett 2020; Sayinli et al. 2022). However, due to the current technological constraints, it is almost mandatory for systems that employ UV (Lundgreen et al. 2019). The electrolysis/electro-chlorination method is second most employed in the secondary treatment in approved systems. The review of the systems that only employ active substances would reveal that this is the most preferred technology (Gerhard et al. 2019; Sayinli et al. 2022). Independent of the adopted technique, these processes undoubtedly require certain equipment and substructure on the ships. Furthermore, the efficient operation of the installed system is another requirement. This could lead to certain liabilities and costs for the ships and corporations. Since the system's cost is around USD 2000.000–500.000 for a single ship (Tokuş 2019), it could be suggested that financial considerations are a determining factor for ship owners. These costs could reach enormous figures, especially for corporations with large fleets. Although the most important criterion for the investor is the investment and operating costs, the ship's region of operation, type, ballast capacity, approval of the system, the dimensions of the system, the space that could be allocated for the system, etc., the process includes several choices and decisions (Vorkapić et al. 2016; Cheng et al. 2019; Tokuş 2019). Shipowners search for methods to solve this obligation introduced by the IMO as soon as possible and select the most adequate costly and complex system (Wang and Corbett 2020; Lakshmi et al. 2021; Sayinli et al. 2022).

The installation of ship ballast treatment systems required by the 'International Convention for the Control and Management of Ships' Ballast Water and Sediments' requires the consideration of several costly criteria and alternatives. Furthermore, the decisions of maritime companies do not only affect their ships and firms, but are also closely associated with the global water ecosystems. It is a typical a decision-making problem that aims to determine the ideal solution by analysing several similar criteria and alternatives (Chou 2007; Ding 2008; Özdemir and Güneroğlu 2015). Likely, a solution that does not employ quantitative methods in a decision-making process that entails several criteria and alternatives that interact and correlate would fail. Thus, a decision problem approach was developed for the issues, processes and the best solution alternatives that a maritime company should consider in selecting a ship ballast water treatment system. The analysis of the problem data led to the adoption of an integrated DEMATEL *(The Decision Making Trial and Evaluation Laboratory)* and ANP *(Analytic Network Process)* method in the study since the existing criteria interacted, the criteria set formed a network, and a holistic approach to the process was required. Economic, ideal and sustainable ship management considerations require an analytical framework based on expert opinions when deciding on a physical ballast treatment system; therefore, the authors of this study focused on determining the necessary criteria for the ideal balast treatment system for ship selection by applying a hybrid MCDM *(Multi Criteria Decision Making)* approach. This study is important as it stresses the connection between the ideal ballast treatment system selection and investment decision management for ships. Moreover, it can contribute to the decision-making process by providing the necessary criteria. There are many ship management and investment decision applications of the MCDM strategies successfully carried out in the literature (Chou and Liang 2001; Ding and Liang 2005; Ding 2008; Çelik and Topçu 2009; Pak et al. 2015; Nguyen 2018; Ren et al. 2018), but none of them focused on the problems emphasised in this study.

The criteria that affect the installation of the treatment system were determined, and the DEMATEL method was employed to graphically describe the correlations between these criteria. Then, the criterion weight and the priority scores of the alternative systems were determined with the ANP method based on the above-mentioned correlations.

2. Material and methodology

To determine the most important criteria affecting an ideal ballast water treatment system decision, a hybrid methodology, combining the decision-making trial and evaluation laboratory (DEMATEL) and analytical network process (ANP), was used. Conventional assessment methods generally take the minimal cost or the maximum advantage as their single index of criteria for measurement (Ting et al. 2004; Vujanovic et al. 2012; Özdemir and Güneroğlu 2015; Özdemir and Güneroğlu 2017). Besides, these approaches may not be adequate for the progressively complicated and various decision-making environments. Thus, to determine the ideal ballast treatment system selection for ships, a hybrid MCDM method, combined with DEMATEL and ANP, was used. Firstly, the formulation of the problem was established, including the main aims and evaluation clusters.

The DEMATEL method was used to evaluate the criteria, which could be potentially effective in determining the ideal ballast water treatment system criteria. The critical impact of each node on the ballast water treatment system selection and the network effect was defined. An initial direct-relation matrix was created based on a pairwise comparison of total-relation matrix values (D + R and D−R), and the criteria were clustered in the form of a critical relative graph by applying the DEMATEL technique (Vujanovic et al. 2012; Wanga and Tzeng 2012; Özdemir and Güneroğlu 2015). The relative graph is necessary for explaining the network structure of the clusters in determining the most influential criteria for an ideal ballast water treatment system decision. The horizontal axis of the digraph shows the strength of the most influential factors, whereas the vertical axis represents the influence type and direction according to the analytical value of each criterion. The inner relations between the two criteria can also be depicted by evaluating the results of the pairwise comparisons of the involved factors. To generate the objective supermatrix of ANP, the network effect should be first built using DEMATEL (Vujanovic et al. 2012; Özdemir and Güneroğlu 2015; Güneroğlu et al. 2016).

A DEMATEL method is a step-wise approach for determining the impact of the main factor involved in the decision-making process by explaining the inner relations of the criteria set and obtaining the main criterion (Yang et al. 2008; Wu and Lee 2011). In DEMATEL, the cause and effect groups are generated from the criteria presented as digraphs (Tzeng et al. 2007; Tseng 2009; Özdemir and Güneroğlu 2015). This technique is widely accepted in solving complex decision-making problems that require causal relationship analysis (Tzeng et al. 2007). In this study, the DEMATEL technique was used according to the available literature (Liou et al. 2007; Chen and Yu 2008; Yang et al. 2008; Tseng 2009; Wanga and Tzeng 2012; Özdemir and Güneroğlu 2015).) The procedure of this technique can be summarised as follows.

Step 1: Calculation of an average matrix needed to create the initial direct-relation matrix is carried out. For quantification purposes, a five-level comparison scale between '0 and 4' is designed to apply the pairwise comparison of the relational effects of each criterion. The aim is to get quantitative information on the judgments ranging from 'no influence' to 'very high influence. For quantification purposes, a five-level comparison scale between '0 and 4' is designed to apply the pairwise comparison of the relational effects of each criterion. The aim is to get quantitative information on the judgments ranging from 'no influence' to 'very high influence'.

Step 2: Normalisation procedure of the initial direct-relation matrix is applied.

Step 3: Calculation of the total-relation matrix is performed using the direct-relation and identity matrices.

Step 4: The sum of the rows and columns in the total-relation matrix 'K' is evaluated to decide the cause and effects of each factor in the entire network. In this step, the sum of rows and columns in the matrix 'K' are formulated as 'D' and 'R' through the following equations:

$$K = [k_{cv}] \quad c, \ v = 1, \ 2, \ 3, \ \ldots n \tag{1}$$

$$D = (Dc) = \left(\sum_{v=1}^{n} k_{cv} \right) \tag{2}$$

$$R = (Rv) = \left(\sum_{c=1}^{n} k_{cv} \right) \tag{3}$$

where 'c' and 'v' are rows and columns of matrix 'K' and 'D' is the sum of the *i*th row in the matrix 'K' and stands for the total-influence send off from criterion 'v' to the other criteria. 'Rv' is the sum of the column that shows the sum of the influence that factor 'c' receives from the other criteria in the matrix 'K'. The sum of (D + R) is the index representing the strength of influence sending and receiving. Furthermore, if (D−R) is positive, then the factor 'c' sends off the influence to the other criteria, and if (D−R) is negative, then the criterion 'c' rather receives the influence from the other criteria.

Step 5: After all, to form a digraph of the pairwise expert evaluating process, a threshold value should be set by the user to remove some negligible influences. In this study, the threshold value was decided by calculating the average value of the elements in the matrix 'K'. Therefore, only the values exceeding the threshold value are shown in the digraph. The digraph is obtained by mapping the 'D + R' and 'D−R'.

The other technique used in this study is ANP, which is a modified form of the analytical hierarchy process (AHP). The ANP technique has received a wide user response in the scientific community due to the logical procedure involved that can include dependencies and feedback using a hierarchical decision network (Wanga and Tzeng 2012; Güneroğlu et al. 2016). ANP can be used for assessing the dependency and feedback rates for each cluster and the entire network by calculating the weight of each cluster in the decision-making process (Vujanovic et al. 2012; Özdemir and Güneroğlu 2015). To overcome the interdependency problem among different clusters, Saaty (2004) suggests using a supermatrix known as the ANP method in the literature (Tseng 2009). In the supermatrix structure, the weight of each matrix element is separately assessed in a network where all the elements of the matrix have relative influences on each other. The supermatrix approximation of the technique is used in deciding the priorities of the decision problem.

In this study, the ANP procedure proposed by Chen and Yu (2008); Saaty (2004); Saaty (2008); Yang et al. (2008); Özdemir and Güneroğlu (2015) and Güneroğlu et al. (2016) has been followed. A step-wise procedure was applied to determine the priorities of the factors involved in the ideal ballast water treatment system criteria. As a first step, the network relation map was generated using DEMATEL and then the total influence matrix 'K' and threshold value 'α' were derived to generate a new matrix called the α-cut total-influence matrix. After normalisation of the α-cut total-influence matrix, a supermatrix was obtained by combining the normalised total influence matrix and the unweighted supermatrix based on the relative influences of each element in the matrix structure. Finally, a stable supermatrix was obtained by taking the limit of the supermatrix to a sufficiently large power for determining the priorities or weights of each criterion.

Table 1. Expert group profile.

# of experts	Expert Profile
10	Senior executives employed in shipping companies with various vessels (General managers, operations manager, technical manager, DPA (Designated Person Ashore)), ship engine technical manager of different ship companies)
7	Naval engineers
6	Different shipyard managers
6	Ship ballast treatment system manufacturing company managers
4	Professors with scientific publications in marine engineering area
4	Ocean going masters employed in different types of merchant ships
Total	**37 experts**

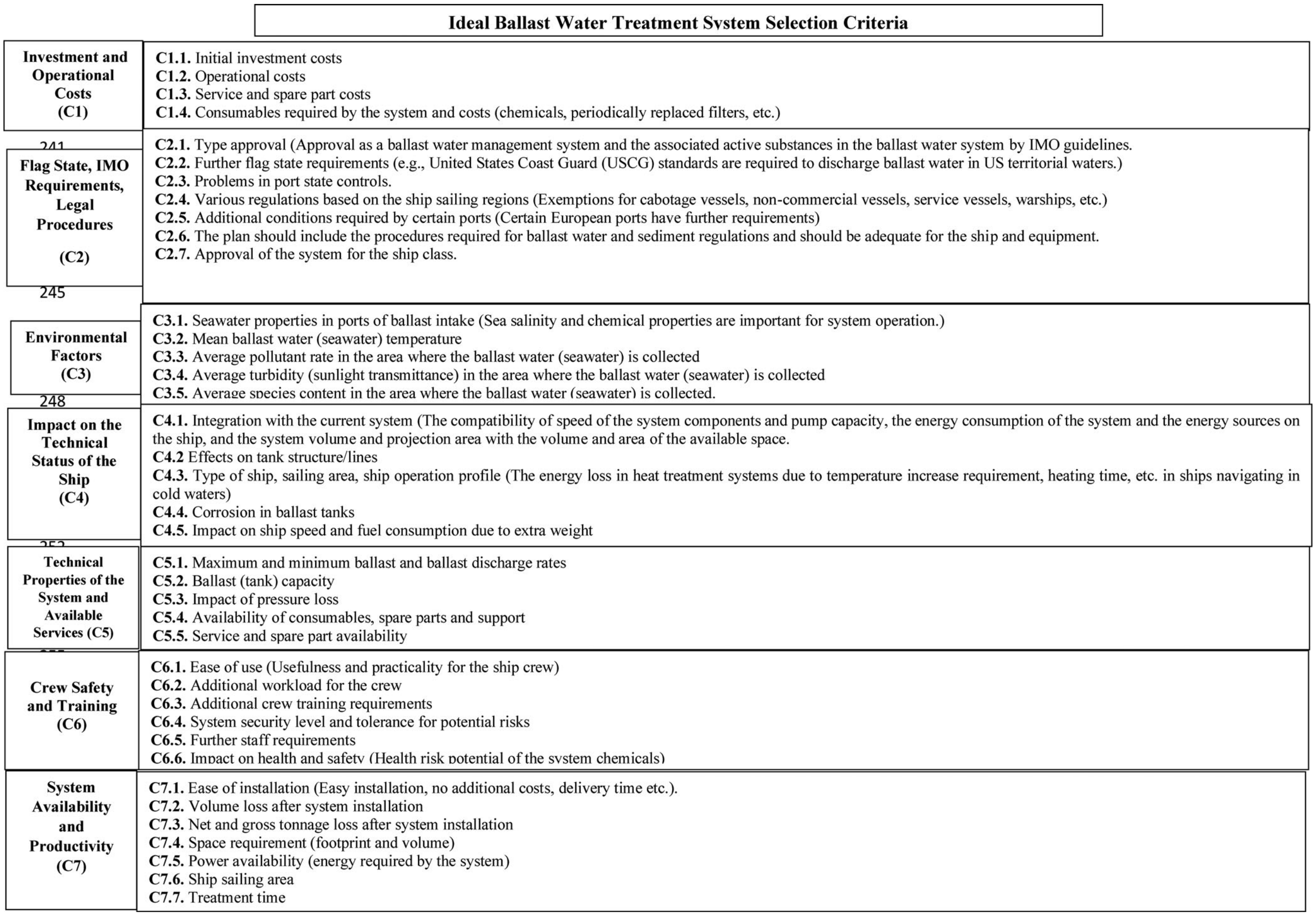
2.1. The case study of the ship ballast water treatment system decision

In this case study, it is assumed that the ship ballast water treatment system problem is a complicated decision that requires an analytical approach based on expert knowledge. The criteria set was evaluated by an expert group for elimination purposes by considering the weight of each criterion. To analyse the data with pairwise comparison matrices, an expert decision-making group with 37 individuals was assigned. The details of the expert group members are presented in Table 1. All quantitative data used in DEMATEL and ANP computations were obtained from the scores given by the expert team. The expert team members were chosen according to their work experience and profession. As the ship ballast water treatment system is largely related to the ship technical management concept, the total number of experts was not equally distributed according to the profession. Therefore, most of the experts were formed by the ship's technical managers. The criteria set for the determination of the ideal ballast treatment system was created according to 'International Convention for the Control and Management of Ships' Ballast Water and Sediments (IMO 2004) and US Ballast Water Management (BWM) Regulations', detailed literature survey as in Figure 1.

Then, to obtain the network relationships of the ideal ship ballast water treatment system criteria, the scores from each questionnaire were used. To determine the relative importance between two criteria, a pairwise comparison scale between '0 and 4' was provided to the expert team members. The relative influences among the criteria were converted to numbers by ranking each comparison between '0 and 4' as 'no influence', 'low influence', 'moderate influence', 'high influence' and 'very high influence'. The total average scores of each expert were calculated, and the average initial direct relational '7 X 7' matrix was generated, as shown in Table 2.

The normalisation process was carried out on the initial direct relational matrix to generate the normalised form of the matrix, which was later used to obtain the total-relation matrix. The total-influential relation matrix is shown in Table 3. The sum of the effects sent off and received by each factor can be seen in Table 3. 'Du' and 'Rv' were calculated according to Equations (2) and (3). The results of 'Du' and 'Rv' are important in quantifying the inner relations between many factors that are potentially effective in the ship ballast water treatment system decision process. An interpretation of those values explains the factor under the influence of some others and the ones dominating the decision network.

An average score for matrix 'K' was computed as a threshold value to omit some negligible values in the matrix, and the result



Ideal Ballast Water Treatment System Selection Criteria	
Investment and Operational Costs (C1)	**C1.1.** Initial investment costs **C1.2.** Operational costs **C1.3.** Service and spare part costs **C1.4.** Consumables required by the system and costs (chemicals, periodically replaced filters, etc.)
Flag State, IMO Requirements, Legal Procedures (C2)	**C2.1.** Type approval (Approval as a ballast water management system and the associated active substances in the ballast water system by IMO guidelines. **C2.2.** Further flag state requirements (e.g., United States Coast Guard (USCG) standards are required to discharge ballast water in US territorial waters.) **C2.3.** Problems in port state controls. **C2.4.** Various regulations based on the ship sailing regions (Exemptions for cabotage vessels, non-commercial vessels, service vessels, warships, etc.) **C2.5.** Additional conditions required by certain ports (Certain European ports have further requirements) **C2.6.** The plan should include the procedures required for ballast water and sediment regulations and should be adequate for the ship and equipment. **C2.7.** Approval of the system for the ship class.
Environmental Factors (C3)	**C3.1.** Seawater properties in ports of ballast intake (Sea salinity and chemical properties are important for system operation.) **C3.2.** Mean ballast water (seawater) temperature **C3.3.** Average pollutant rate in the area where the ballast water (seawater) is collected **C3.4.** Average turbidity (sunlight transmittance) in the area where the ballast water (seawater) is collected **C3.5.** Average species content in the area where the ballast water (seawater) is collected.
Impact on the Technical Status of the Ship (C4)	**C4.1.** Integration with the current system (The compatibility of speed of the system components and pump capacity, the energy consumption of the system and the energy sources on the ship, and the system volume and projection area with the volume and area of the available space. **C4.2** Effects on tank structure/lines **C4.3.** Type of ship, sailing area, ship operation profile (The energy loss in heat treatment systems due to temperature increase requirement, heating time, etc. in ships navigating in cold waters) **C4.4.** Corrosion in ballast tanks **C4.5.** Impact on ship speed and fuel consumption due to extra weight
Technical Properties of the System and Available Services (C5)	**C5.1.** Maximum and minimum ballast and ballast discharge rates **C5.2.** Ballast (tank) capacity **C5.3.** Impact of pressure loss **C5.4.** Availability of consumables, spare parts and support **C5.5.** Service and spare part availability
Crew Safety and Training (C6)	**C6.1.** Ease of use (Usefulness and practicality for the ship crew) **C6.2.** Additional workload for the crew **C6.3.** Additional crew training requirements **C6.4.** System security level and tolerance for potential risks **C6.5.** Further staff requirements **C6.6.** Impact on health and safety (Health risk potential of the system chemicals)
System Availability and Productivity (C7)	**C7.1.** Ease of installation (Easy installation, no additional costs, delivery time etc.). **C7.2.** Volume loss after system installation **C7.3.** Net and gross tonnage loss after system installation **C7.4.** Space requirement (footprint and volume) **C7.5.** Power availability (energy required by the system) **C7.6.** Ship sailing area **C7.7.** Treatment time

Figure 1. Ideal ballast water treatment system selection criteria (This figure is available in colour online).

for the threshold value was set as 0,556. The sum of the influences sent and received by each factor is shown in Table 4. Criteria that stand as net causes or effects are depicted as a digraph in Figure 2 to map the network relationships.

According to the results shown in Table 4, the C4 (Impact on the Technical Status of the Ship) factor has the highest score (8,282) of D + R. Therefore it can be accepted that it is the most important dimension of the case study, whereas C6 (Crew Safety and Training) criterion has been considered the least important in terms of 'Du + Rv' values (7, 298). To explain the cause-effect relationships and the importance of each factor involved in the ship ballast water treatment system criteria assurance problem, a digraph with a horizontal axis (D + R) representing the importance level and a vertical axis (D−R) as for relations is given in Figure 2. Moreover, the final decision on the ideal ship ballast water treatment system assurance will depend on real numbers represented by 'Du' and 'Rv' values.

Table 2. Direct initial matrix.

Criteria set	C1	C2	C3	C4	C5	C6	C7
C1	0	0,234	0,355	0,254	0,147	0,181	0,310
C2	0,219	0	0,125	0,304	0,312	0,369	0,297
C3	0,285	0,315	0	0,289	0,167	0,278	0,121
C4	0,361	0,145	0,367	0	0,347	0,314	0,364
C5	0,125	0,198	0,271	0,147	0	0,197	0,189
C6	0,198	0,254	0,326	0,304	0,355	0	0,254
C7	0,304	0,314	0,187	0,185	0,268	0,121	0

Table 3. Total-influential relation matrix K.

Criteria set	C1	C2	C3	C4	C5	C6	C7	Rv
C1	0, 587	0,752	0,847	0,384	0,841	0,904	0,874	4,602
C2	0,716	0, 468	0,301	0,527	0,781	0,603	0,369	3,297
C3	0,424	0,727	0, 837	0,814	0,488	0,491	0,640	3,584
C4	0,814	0,625	0,610	0, 749	0,703	0,935	0,911	4,598
C5	0,562	0,904	0,314	0,901	0, 834	0,408	0,351	3,44
C6	0,314	0,417	0,911	0,729	0,510	0, 874	0,439	3,32
C7	0,847	0,870	0,913	0,329	0,817	0,637	0, 915	4,413
Du	3,677	4,295	3,896	3,684	4,14	3,978	3,584	–

According to Figure 2, the C2 *(Flag State, IMO Requirements, Legal Procedures)*, C3 *(Environmental Factors)*, C5 *(Technical Properties of the System and Available Services)*, C6 *(Crew Safety and Training)* criteria were net causes, whereas the effect groups (receivers) with negative (D–R) values were the C1 *(Investment and Operational Costs)*, C4 *(Impact on the Technical Status of the Ship)* and C7 *(System Availability and Productivity)* criteria set. Considering further the causal relationships map, it can be seen that the C2, C3, C5 and C6 criteria were the most important factors that should be considered when making decisions on an ideal ship ballast water treatment system. It was also clear from the digraph map that all factors were influenced or mutually interacted when deciding on the ideal ship ballast water treatment system.

To decide on the priorities that affect the ideal ship ballast water treatment system criteria, a normalised total-relation matrix was used as an input to the ANP process. As the cluster network map of the factors was mapped with the DEMATEL technique, it was necessary to know the importance or weight of each criterion involved in the decision-making process. Therefore, the total influence matrix was computed as depicted in Table 5.

Table 4. Sum of influences given and received on each criterion.

Criteria	Du + Rv	Du−Rv
C1	8,279	−0,925
C2	7,592	0,998
C3	7,480	0,312
C4	8,282	−0,914
C5	7,580	0,700
C6	7,298	0,658
C7	7,997	−0,829

Table 5. Normalised total-influence matrix.

Criteria set	C1	C2	C3	C4	C5	C6	C7
C1	0, 823	0,014	0	0,027	0	0	0,038
C2	0,238	0, 037	0,141	0,136	0,092	0	0,201
C3	0,115	0,841	0, 032	0,034	0,104	0,108	0
C4	0,094	0,314	0,201	0	0,221	0,050	0,031
C5	0,307	0,065	0,076	0,311	0	0,078	0,238
C6	0	0,126	0	0,401	0,319	0, 211	0,132
C7	0,163	0,052	0,207	0,227	0,231	0,342	0, 401

The digraph map of the network relation and importance level can be further investigated to determine the quantitative information on the major criteria set that has the highest influence on the process. It was evident from Figure 2 that the criteria were the most influential and should be ranked as the first when trying to make decisions on an ideal ship ballast water treatment system. Furthermore, C1 *(Investment and Operational Costs)* and C4 (*Impact on the Technical Status of the Ship)* factors had almost the same level of importance in terms of ship ballast water treatment system selection based on expert knowledge. Therefore, the most influential criteria set that consists of C4, C1 and C7 main and related sub-criteria were analysed by the ANP to decide on the weights or priorities. At this stage, the weighted supermatrix was derived by combining the α-cut total-influence matrix and the unweighted supermatrix. Finally, a resultant matrix with quantitative information on each criterion can be derived by raising the limit to sufficiently high power on the weighted supermatrix, as shown in Table 6.

3. Results and discussion

A hybrid MCDM approach, combined with DEMATEL and ANP, was successfully implemented to solve a ship technical investment planning problem. In this case, the ship ballast water treatment system was evaluated to help decision-makers, ship owners or ship technical managers on the main drivers effective in the ship-technical investment problem. The MCDM approach offers an opportunity to evaluate complex decisions based on expert knowledge and quantitative data. This technique was widely used in technical shipping applications such as in the shipping business processes (Ding and Liang 2005; Çelik and Topçu 2009; Özdemir and Güneroğlu 2015; Özdemir and Güneroğlu 2017), shipping technology application management problem (Nguyen 2018), performance evaluation problem for shipping and port companies (Chou and Liang 2001; Ding 2008; Pak et al. 2015), port selection problem (Chou 2007; Hsu et al. 2020), ship accident assessment (Özdemir and Güneroğlu 2015). Therefore, it was proved that the operational management of technical shipping problems can be analytically solved by an appropriate MCDM strategy. It was observed that the integrated DEMATEL and ANP approach was almost never employed in the maritime literature. Apart from the study conducted by Özdemir and Güneroğlu (2015), which investigated the human factor in ship accidents with the DEMATEL and ANP approach, no other study in the maritime literature included this approach.

Criteria clusters that were very effective in the ship ballast water treatment system problem appeared in order of importance. The related subcriteria were ranked according to their relative scores or weights. Based on the supermatrix in Table 6, the sub-criteria with the highest scores were C11, C41, C71, C12, C73, C13, C45, C46, C14, C44, C43, C75, C42, C76, C72, C74 and C77. Moreover, the top five priorities in the evaluation system were C11 (initial investment costs at 8,90%), C41 (integration with the current system.at 8,10%), C71 (ease of installation at 7,40%), C12 (operational costs at 6,80%), C73 (net and gross tonnage loss after system installation at 6,40%) and the least important criterion was C77 (treatment time at 1, 10%). The first three major factors involved in ship ballast water treatment system assurance appeared as ‘impact

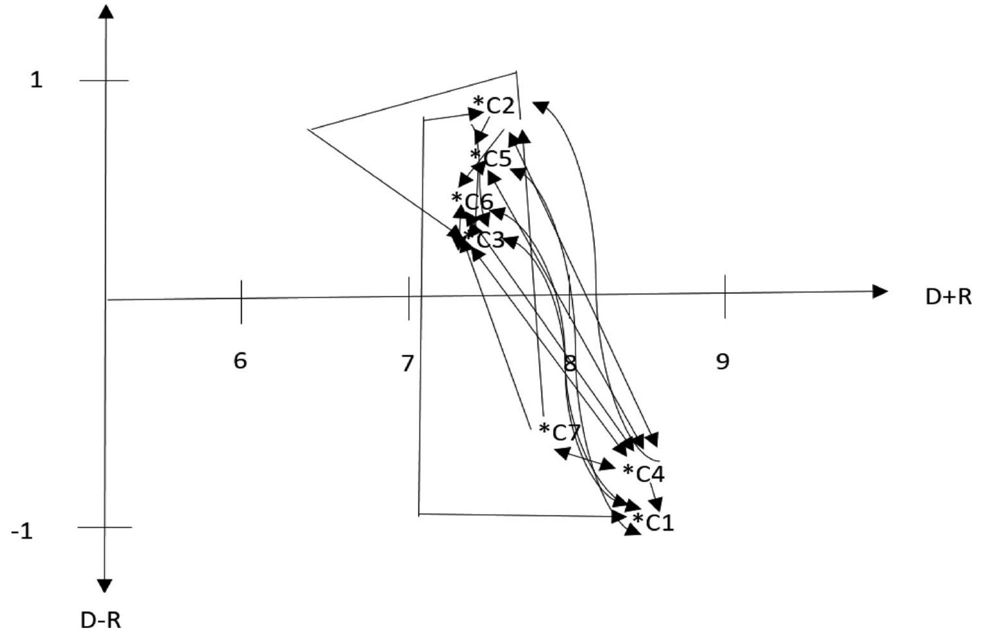


Figure 2. Digraph map of the importance and relation level (This figure is available in colour online).

Table 6. The final supermatrix with relative weight of each criterion.

	C11	C12	C13	C14	C41	C42	C43	C44	C45	C46	C71	C72	C73	C74	C75	C76	C77
C11	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**	**0,089**
C12	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**	**0,068**
C13	0,058	0,058	0,058	0,058	0,058	0,058	0,058	0,058	0,058	0,058	0,058	0,058	0,058	0,058	0,058	0,058	0,058
C14	0,042	0,042	0,042	0,042	0,042	0,042	0,042	0,042	0,042	0,042	0,042	0,042	0,042	0,042	0,042	0,042	0,042
C41	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**	**0,081**
C42	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028	0,028
C43	0,036	0,036	0,036	0,036	0,036	0,036	0,036	0,036	0,036	0,036	0,036	0,036	0,036	0,036	0,036	0,036	0,036
C44	0,038	0,038	0,038	0,038	0,038	0,038	0,038	0,038	0,038	0,038	0,038	0,038	0,038	0,038	0,038	0,038	0,038
C45	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056	0,056
C46	0,049	0,049	0,049	0,049	0,049	0,049	0,049	0,049	0,049	0,049	0,049	0,049	0,049	0,049	0,049	0,049	0,049
C71	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**	**0,074**
C72	0,021	0,021	0,021	0,021	0,021	0,021	0,021	0,021	0,021	0,021	0,021	0,021	0,021	0,021	0,021	0,021	0,021
C73	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**	**0,064**
C74	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018	0,018
C75	0,031	0,031	0,031	0,031	0,031	0,031	0,031	0,031	0,031	0,031	0,031	0,031	0,031	0,031	0,031	0,031	0,031
C76	0,026	0,026	0,026	0,026	0,026	0,026	0,026	0,026	0,026	0,026	0,026	0,026	0,026	0,026	0,026	0,026	0,026
C77	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011	0,011

Note: The bold values represent the first 5 criteria with the highest weights.

on the technical status of the ship', 'technical properties of the system and available services' and 'investment and operational costs' criteria. It should be stressed that 'investment and operational costs' and 'impact on the technical status of the ship' factors have almost the same level of importance according to the experts' evaluations.

Selection of the right ship ballast water treatment system is a costly process. The installation of an average system costs around USD 500,000–750,000 (Tokuş 2019; Doğru et al. 2021). Such high costs could lead to financial problems for small maritime companies. Thus, a correct approach should be adopted before selecting a system. The present study findings demonstrated that the highest priority criterion was C1 (investment and operating costs). This revealed that the decision-makers mostly emphasised the investment and operating costs. Furthermore, the study findings also revealed that the selected system should be sustainable, compatible with the ship conditions, and meet the regulations.

Previous studies on ship ballast water were mostly on environmental and marine ecosystems (Gollasch et al. 2000; Cohen and Dobbs 2015; Lundgreen et al. 2019; Wang and Corbett 2020; Lakshmi et al. 2021; Wang et al. 2021) and the operation of the ballast treatment systems (Calvar et al. 2018; Gerhard et al. 2019; Makkonen and Inkinen 2021; Sayinli et al. 2022). Thus, it would be possible that ship owners, operators and companies could experience difficulties in making such high investment decisions, and the studies in the literature were insufficient to support these decisions.

The results of the study were promising in terms of quantitative ship investment management strategy and can be extended further to cover some other shipping management problems such as ship main or auxiliary engine selection problems, evaluating causes of exhaust gas emissions of ships, port vehicle selection problems, determining of strategic management models for maritime companies, etc.

4. Conclusion

Ballast water treatment systems include different combinations of technologies developed based on certain mechanical, physical and chemical principles. Although the systems are based on similar principles, the components of these systems are produced by various manufacturers. Thus, the components with similar principles have different efficiencies, capacities and costs. The selection of the ballast water system should include the analysis of the system's suitability to ship and operational properties, and the factors that affect the system performance. The present study aimed to develop proactive solution recommendations for ship owners to select the ideal ballast water treatment system for their ships with a quantitative approach and an integrated analysis of all factors. Furthermore, it was also demonstrated that the DEMATEL and ANP method, a different approach to MCDM, which was rarely employed in the maritime literature, could be adopted successfully in decision-making problems in this field. However, the authors hope that the study findings would assist ship owners and technical project managers and support maritime investment management plans through quantitative data.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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