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Evaluation of ballast water treatment systems from the perspective of expert seafarers' ship experiences

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Summary

Until recently, the selection of ballast water treatment (BWT) systems was based on a predetermined set of criteria that did not include evaluations for system utilization due to lack of experience. The experience-building phase for the systems began, especially with the entry of the Ballast Water Management Convention into force. For effective assessment and decision-making, the evaluations of expert seafarers responsible for using ballast water treatment systems on-board ships are of paramount importance.

This study was completed by evaluating the experience and evaluations of 50 expert seafarers (24 deck personnel and 26 engine personnel) working in a Turkish maritime company in three phases to contribute to the decision-making and system evaluation processes: 1- The failure reports written by the ship personnel of the maritime company were examined, and bilateral interviews with expert seafarers working on these tankers were held; 2- an online questionnaire was prepared and presented to seafarers; 3Analytic hierarchy process (AHP) was used to obtain a common perspective of the seafarers.

In this study's first phase, 'ideal system characteristics' were determined. Based on these characteristics, an online questionnaire was prepared in the second phase of this study and presented to seafarers. In the third phase, a set of six criteria was developed, and the Analytic Hierarchy Process (AHP) was used to obtain the common perspective of 50 participants. Pairwise comparisons revealed that 'Rare alarms and malfunctions' was the most important criterion from the perspective of all seafarers and UV-type BWTSs were 1.76 times more preferable than the electrochemical (El-Chem) type BWTSs as a common approach.

Keywords: Ballast water treatment; BWTS evaluation; UV systems; El-Chem systems; analytic hierarchy process

1. Introduction

The role of ships in the transportation of alien species to different geographies by various means has been known for many years. Ballast water, which is among the various vectors on the ship, has the most significant share in this transportation. The ecological and public health impacts and potential harms of alien species translocation and its direct or indirect costs have been documented in different parts of the world for decades [1–11].

Every year, 3.1 billion ballast water is discharged into different ports [12]. The International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention), which was ratified under the auspices of the International Maritime Organization (IMO) and entered into force on September 8, 2017, aims to prevent or at least minimize the introduction of Harmful Aquatic Organisms and Pathogens (HAOP) on international voyages by managing ballast water within certain rules. As defined in the IMO BWM convention, '*Harmful Aquatic Organisms and Pathogens' means aquatic organisms or pathogens which, if introduced into the sea, including estuaries, or into fresh water courses, may create hazards to the environment, human health, property, or resources, impair biological diversity or interfere with other legitimate uses of such areas'* [13].

The IMO BWM convention requires all ships (with some exceptions and exemptions defined in Article 3) greater than 400 GRT sailing internationally to meet the D-2 discharge standard of the convention within a certain time frame until September 8, 2024 [13]. In addition, the United States of America, which is not a party to the IMO BWM Convention, has developed its own Legislation (i.e., The U.S. Coast Guard Final Rule on Standards for Living Organisms in Ships' Ballast Water Discharged in U.S. Waters). The 'Final Rule' became effective in June 2012 and applies to all vessels discharging ballast water in U.S. waters that were taken on outside the U.S. and Canadian Exclusive Economic Zone. Along with this national legislation stipulated by the Final Rule, state-based rules form the framework of US regulations [14]. In the field of ballast water management, both the IMO BWM Convention and the US practices are the two most effective legal regimes at the international level. The practical equivalent of meeting the requirements of both regimes by ships is to equip them with ballast water treatment systems (BWTSs) approved according to the relevant legal regime.

The majority of existing ballast water treatment systems (BWTSs) include mechanical pre-treatment (mostly screen filters, disk filters, and hydrocyclones) followed by secondary treatment, such as ultraviolet (UV) irradiation, electrochemical (El-Chem) methods (i.e., direct electrolysis and electrochlorination), heat treatment, and chemical injection. The pre-treatment stage aims to increase the efficiency of secondary treatment, mostly by removing organisms and particles from ballast water. The dimensions of particles and organisms that can be removed from the ballast water vary by the pre-treatment unit employed in the system [15]. However, there are also systems on the market that do not include a pre-treatment stage [16]. The purpose of the secondary treatment is to ensure that the ballast water meets the desired discharge standards. The efficiency of each method used in ballast water treatment systems in terms of meeting the standards varies depending on different technological and environmental factors and targeted organisms [15,17]. Among these various methods, UV and El-Chem methods are the most utilized techniques in the market[16,18]. The UV systems rely on UV irradiation's ability to disrupt the organisms' cell components [19–21]. The El-Chem systems use El-Chem reactors to produce disinfectants, such as chlorine (Cl_2) gas and hypochlorous acid (HOCl) from seawater. In some systems, a portion of the main ballast stream is passed through electrolysis cells to produce a disinfectant containing high amounts of chlorine species and then injected into the entire ballast stream [22–24], while in other systems, the entire ballast stream is subjected to electrochemical treatment to produce a lower concentration of chlorine species sufficient to achieve disinfection [25–28].

IMO BWM Convention requires all installed BWTSs to have a Type Approval Certificate granted following Guidelines for Approval of Ballast Water Management Systems (G8) (revised in 2016 [29] and also adopted as Code for Approval of Ballast Water Management Systems in 2018 (BWMS Code)) [30]. In the IMO Type Approval process, a subcategory of BWTS is also defined as a '*ballast water treatment system that makes use of an active substance.*' The BWM Convention defines an active substance as '*a substance or organism, including a virus or a fungus, that has a general or specific action on or against Harmful*

Aquatic Organisms and Pathogens' [13]. If a system belongs to this category, a second process is included in the above-mentioned G8/BWMS Code approval process to ensure the acceptability of the active substance for ship safety, human health, and the environment. For this additional process, the guidelines for the *Procedure for approval of ballast water management systems that make use of active substances* (G9) should be followed. What this means in practice is that the residual active substances (these are called total residual oxidants (TROs)) in ballast water treated by a BWTS must be reduced to an acceptable level, which in most cases is reached by an additional treatment stage added to the system before discharge. This is because when released in the marine environment, TRO compounds can react in seawater to form secondary oxidants that are harmful to marine organisms. It should be noted that this stage is necessary even if the chemical required for disinfection is produced on board, such as El-Chem systems.

There are several BWTSs on the market at different prices. According to the International Chamber of Shipping, the economic cost of BWTS installation is typically US$1-5 million per ship [31]; the operational costs of the system are also affected by the treatment method as well as other factors [32,33] and methods used in the systems have their advantages and disadvantages regarding many reasons, such as environmental acceptability, ballast tank corrosion, holding time requirement, and safety [34–36].

From the date of entry into force of the IMO BWM Convention, newly built ships must be launched equipped with IMO Type Approved BWTSs, and existing ships must be equipped with BWTS by the established schedule ending on September 8, 2024 [16]. Therefore, thousands of ships have been equipped with ballast water systems to date, including earlier installations. Decisive factors of the installations are not limited to parameters affecting efficiency and price. The size and energy requirements of the systems require technical and structural compatibility for ships. The stage at which the ballast water treatment will be carried out, and the holding time in the tank for efficient treatment require the compatibility of the systems with ship operations and navigational characteristics. System capacity should be considered for technical, structural, and operational compatibility aspects.

The presence of such a variety of criteria makes BWTS selection a highly complex issue. Many multi-criteria decision-making models have been proposed to determine the right alternative [37–44]. Each model was developed using a varying number of parameters in different combinations. When these studies are examined, the parameters can be classified into five main categories:

- Technical parameters (energy requirement, system dimensions, system mass, gas-tight design)
- Parameters related to operational and voyage characteristics of the ship (system capacity, duration of treatment, treatment while traveling in port or at sea, adaptation to harsh environments)
- Parameters related to costs and manufacturer reliability (installation cost and operating costs, manufacturer longevity, system durability, and quality)
- Social aspects (human risk, ecological risk, waste generation, pollution footprint)
- Legal aspects (Approvals and approval procedures)

As using onboard systems is relatively new, it has not been possible so far to effectively assess onboard experience in the decision-making process. However, the comprehensive ballast water sampling study conducted by Bailey et al. (2022), which evaluated ballast water samples from 29 different vessels calling at Canadian ports, demonstrates the importance of crew experience and training and shows that inadequacies in the operation and maintenance of installed systems can lead to ballast water discharge limit exceedances [45]. Ballasting at ports with challenging water quality (PWCQ) is another issue regarding the proper operability of the BWTSs. In the case of sediment load, the BWTS testing requirements of both IMO (>50 mg/L) and USCG (>24 mg/L) may be far below the real-life conditions of some ports. The outcomes of the Experience-Building Phase (EBP) established by IMO show that when the design limitations of the system are exceeded by the total suspended sediment (TSS) content in the port water, BWTSs may fail or the crew may choose to bypass BWTS [46,47].

The crew on board is responsible for the maintenance and repair of BWTSs. On the other hand, fatigue, training, and complex automation are among the human factors with a considerable effect on ballast water management operations [48]. The study by Gerhard et al. (2019) demonstrates the importance of prioritizing simple BWTSs in the decision-making process[18]. Given these considerations, the importance of assessing seafarers' experiences in the decision-making process becomes apparent.

However, the literature survey of the authors of this actual study reveals that the studies on BWTSs mostly depend on the laboratory work on the technical and environmental efficiency of the systems with a limited number of studies based on onboard experiences BWTSs [39,45]. To the authors' knowledge, the focus of previous studies regarding onboard experience was on the environmental performance of the systems and they did not contain a detailed analysis of seafarers' operational experiences with BWTSs.

Aiming to contribute to filling the aforementioned gap regarding the human factor, this study presents an analysis of the experiences of seafarers working in a Turkish shipping company. In line with this purpose, in this study;

1. Problems encountered by seafarers while using UV and El-Chem systems were identified.
2. A set of criteria for the evaluation of ballast water treatment systems from the perspective of expert seafarers was identified, and the criteria were prioritized in relation to the experience of users on board the ship.
3. Using UV and El-Chem systems on board the ship was evaluated in line with the determined criteria and the experience of the seafarers.

This study is different from previous studies in the literature in that it focuses on the experiences of real users of the system and aims to contribute to filling the current gap in the literature and to support the development of more realistic decision-making processes. Shipowners can benefit from user experiences when deciding on the ballast systems they will install on their ships; system developers can review user experiences and preferences for the development of BWTSs. In addition to all these, seafarers sometimes tend to bypass the BWTS to avoid wasting time in case of problems in the systems during ballast/ballasting operations [39] and compromise ballast management. These and similar studies will contribute to minimizing the problems experienced by ships as much as possible and will support a more successful ballast water management at the global level.

2. Methodology

This study was conducted in three successive phases, as shown in the workflow diagram (Fig. 1). In the diagram, the thin blue arrows represent the feeds within and between the phases and the thick red arrows represent the feed for the final evaluation.

In the first phase of this study, the failure reports written by the ship personnel of the maritime company were examined, and bilateral interviews with expert seafarers working on these tankers were held. The main objective of this first phase was identifying the most prominent problems regarding using El-Chem systems and UV systems and determining the characteristics of an ‘ideal BWTS’ from the seafarers’ perspective.

In the second phase, based on the seafarers' common criteria for 'ideal BWTS,' an online questionnaire was prepared and presented to seafarers of the maritime company, and 50 of them responded. The seafarers were asked to rank the 'ideal system characteristics' and evaluate the UV and El-Chem systems in line with these characteristics. In the third phase, to obtain a common perspective of 50 seafarers, the systems were evaluated by the analytic hierarchy process (AHP). First of all, a set of criteria for the evaluation of ballast water treatment systems from the perspective of expert seafarers was identified, the criteria were weighted using AHP and an overall evaluation was obtained for UV and El-Chem systems.

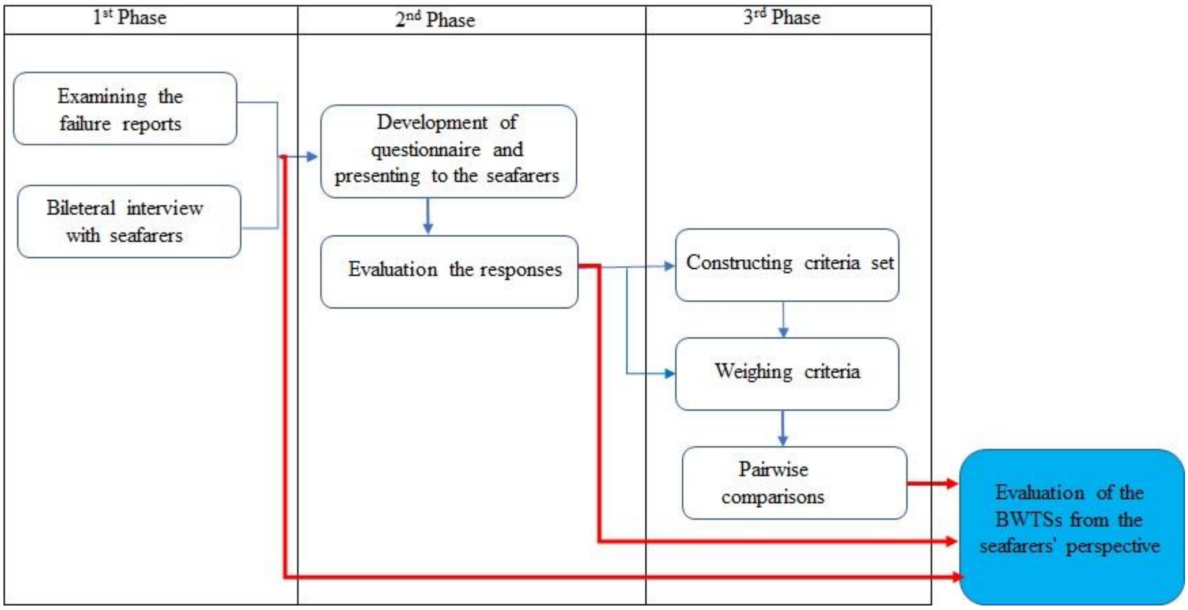

Fig. 1 The workflow of this study

The results of the first two stages were used to create the criteria set, weigh the criteria, and make pairwise comparisons. The analytic hierarchy process is used as a tool in this phase of this study. Although there are several alternatives for multi-criteria decision analyses (MCDA), the problem addressed in this study is relatively simple and AHP is sufficiently used to analyze the problem within the content of this study. AHP provides significant convenience to the users regarding mathematical operations and intelligibility [49] while reducing complex problems to a simple and very flexible model, providing an easily applicable decision-making methodology [50]. The AHP method also plays an important role in quantitative and qualitative or objective and subjective evaluations, and with this method, the overall view of the problem is easily represented [51].

The analytic hierarchy process is a multi-criteria decision-making method that goes back to Thomas L. Saaty's published work in 1972, and since then, it has been widely used for various multi-criteria decision-making problems [52]. AHP transforms complex problems into a hierarchical structure and is based on pairwise comparisons [53]. The values obtained as a result of the comparison are called the pairwise comparison matrix. After these matrices are analyzed, it reveals which of the two criteria being compared is more important and preferable. AHP evaluates the problem in a multi-layered hierarchical structure. The decision decomposes the problem into layers in a hierarchical structure. Thus, the problem is reduced to different sub-problems. The solution to the decision problem is reached by solving the reduced sub-problems.

In this study, comparison of judgments was quantified using Saaty's fundamental scale of 1-9 and the pairwise comparison matrix was checked if it satisfied Saaty's consistency condition (Table 1) as follows [54]:

$$C.R = \frac{C.I}{R.I} < 0.1 \tag{1}$$

In the equation given above, *C. R* is the consistency ratio, *C. I* is the consistency index, and *R.I* is the average random index. Here, *C. I* is calculated as follows:

$$C.I = \frac{\lambda_{max} - n}{n-1} \tag{2}$$

where λ_{max} is the highest eigenvalue matrix of the pairwise comparison matrix, and *n* is the size of the matrix.

Table 1 Random Index [54]

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

2.1 Data Acquisition and Collection

The primary data source of this study was the expert seafarers themselves, who are currently employed on six tankers of a Turkish maritime company. These six tankers were installed with three different BWTSs. However, the working experiences of the seafarers were not limited to these six tankers and three BWTSs only. The manufacturers of the BWTSs that the seafarers reported they had experience with are Alfa Laval, Cathelco, Desmi Ocean Guard, Erma First, Headway Technology, Hyundai Heavy Industries, Panasia, Samsung Heavy Industries, Techcross, and Wartsila (in alphabetical order).

The secondary data source of the study was the failure reports written by the ship personnel of the maritime company. The failure reports were limited to three BWTS installed on the tankers. Due to the company's privacy policies, the name of the company and the brands of the systems used will not be disclosed. Instead, the systems will be named after their technology.

Two of the ships were installed with full-stream electrochemical technology-based BWTSs of the same brand (El-Chem 1), while four of the systems were installed with UV-based BWTSs of two different brands (UV-1 and UV-2). The maritime company integrated El-Chem 1 brand BWTSs into its sister ships built in 2015. In 2019, the company integrated UV-1 brand BWTSs into its tanker ships of the same tonnage. Depending on the experiences gathered since 2015, the company decided to install UV systems on its two existing tankers of different tonnages built before 2013. However, due to economic reasons, the company decided on the UV-2 brand. The capacities of the ships and BWTSs owned by the maritime company are summarized in (Table 2).

Table 2 BWTS installed on the company's ships

BWTS	Capacity	New-built/retrofit	On-board experience with the system since
El-Chem 1	20 000 DWT	New built	2015
El-Chem 1	20 000 DWT	New built	2015
UV-1	20 000 DWT	New built	2019
UV-1	20 000 DWT	New built	2019
UV-2	6 000 DWT	Retrofit	2021
UV-2	50 000 DWT	Retrofit	2021

3. Results

3.1 Outcomes of the failure reports and bilateral interviews

The maritime company has been using El-Chem 1 on two of its ships since 2015 and has been using UV-1 BWTSs on two tanker ships since 2019 and UV-2 BWTSs on two tanker ships since 2021. Failure reports covering the experience gained until 2022 with the systems on board the tankers were examined and in parallel, bilateral meetings were held with expert seafarers working on these tankers. The problems identified regarding the use of El-Chem type and UV-type BWTSs are summarised below.

The problems related to filtering equipment in the pre-treatment stage of the systems: Although the mesh sizes of the filters of different BWTSs in are varying dimensions, the bilateral interviews mainly pointed to the clogging problem of filters. In filters, self-cleaning features are used, but during cleaning, the ballast water treatment capacity decreases and the system cannot clean itself completely. In most cases, cargo loading-unloading operations are affected. Therefore, in many cases filters, which are used especially in large tonnage ships, are removed and cleaned by the seafarers. This process is tiring for seafarers and may expose them to chemicals. On the other hand, automatic back flushing performance also changes by the BWTSs and looking at the UV-based BWTS filters on board the company's vessel in question, it appears that the clogging problem is not only related to the mesh size but also related to the automatic performance of the system. The UV-1 system has 20 μm filters, while the UV-2 system has 50 μm filters. However, UV-1 has an integrated backflush pump and clogging is not a big problem for UV-1 as it is for UV-2.

The problems related to using El-Chem type BWTSs: The El-Chem system consists of several different pieces of equipment, usually located in various parts of the ship and taking up a lot of space in total. This poses a challenge for seafarers in the event of a breakdown and is also tiring during operations and routine checks. Also, as the system consists of many pieces of equipment, electrical failures occur frequently. In addition, the ship crew is required to handle different chemicals although the disinfectant chemical is generated onboard. The system is complex and involves specific hazards, so ship crews need more training.

General maintenance of El-Chem systems is also complex and tedious for seafarers. For example, TRO (Total Residual Oxidant) control of ballast water requires chemical solutions. The need to use this solution varies depending on the frequency of the ballasting operation and the water quality of the port where this operation takes place. The shipping company provides a limited number of solution packages at a time, to be supplied when they run out. On the other hand, the solutions expire within three months of opening the packs, which requires regular monitoring of the solution stock by the crew. However, among all systems on-board ships, BWTSs lag behind regarding priority for seafarers. In addition, the shipping company, like others, frequently changes its crew as a matter of company policy. Indeed, the control and supply of the solution stock may be neglected by the outgoing crew and become a problem for the new crew.

Also, since the pipes of the TRO sensor unit are thin, the solutions used may cause clogging of the pipes. Additionally, due to the corrosive properties of seawater, in cases where the unit pipes are punctured, seawater may damage the electronic parts inside the unit. The solenoid valves of the neutralization unit used in the deballast operation are clogged due to the chemical used. Cleaning the solenoid valves before the operation reduces the possibility of clogging, but it causes extra time and labour loss, especially for the personnel on ships with frequent loading operations.

The corrosive property of seawater is also a problem for the unit where electrolysis takes place. The manufacturers supply chemical washing systems for this corrosion; however, these chemical systems are not very efficient for cleaning the electrolysis unit. For this reason, the electrolysis unit may need to be dismantled and cleaned in chemical liquid outside for at least one day. This extra workload, which is tiring for seafarers, also brings seafarers into contact with chemicals. The excess heat is also another problem regarding the electrolysis units. The unit needs to be cooled and in ships with a problematic general cooling system, the heating of this unit causes other equipment to stop.

In general, since more problems occur in such systems, the past alarm list of the system is longer. This creates a wrong impression about the ship for the inspectors coming to the ship at various periods.

The problems related to using UV-type BWTSs: For some brands of BWTS equipment, UV lamp replacement is done frequently. As a result of the deformation of the outer sleeves of the UV lamps, the direct contact of seawater to the lamp causes the driver unit of the lamp to burn.

Compressed air usage is high for some brands of BWTS equipment. Therefore, it causes the ship's service air compressor or main air compressor to work more.

Air-electric controlled actuators on the system circuits may jam or fail to operate.

3.1.1 The properties of an ‘ideal BWTS’ from seafarers’ perspective

As a result of the evaluation of the problem areas of both El-Chem and UV BWTSs, the following properties were determined for an ‘ideal BWTS’ to be used on board;

- No requirement for preparation before ballasting
- Requirement for little training before use
- Small footprint and simplicity of equipment
- Convenience for routine checks during operation
- No use of chemicals
- Easy maintenance
- Ease of operational use
- Rare alarms and malfunctions

3.2 The survey study

For the survey study, a questionnaire was prepared mainly based on the properties identified in the first stage, and this questionnaire was presented to expert seafarers currently working on board in the Turkish maritime company. A total of 50 of these seafarers (24 deck and 26 engine crew) responded to the questionnaire (Table 3). Participants’ experience of working with El-Chem and UV systems is summarized in Fig. 2.

Table 3 The personnel

Department	Position	Number
Deck	Master	13
	Chief officer	11
Engine	Chief engineer	13
	Second engineer	8
	Electrical officer	5
TOTAL		50

The questionnaire consisted of two main sections. In the first section, the seafarers were asked to rank the properties of the ‘ideal BWTS’ in order of importance from 1 to 8 (i.e., 8 points for the property with the highest importance and 1 point for the property with the lowest importance).

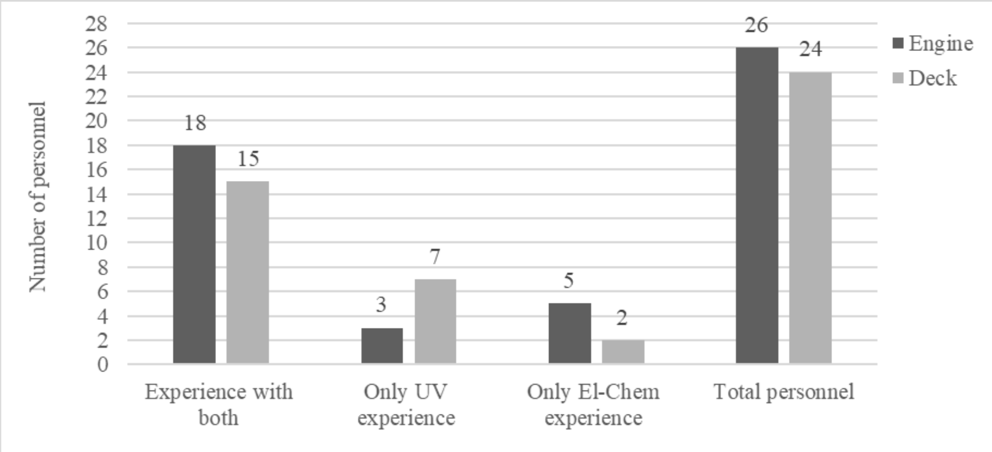

Fig. 2 The experiences of the respondents with BWTS types

The answers in this section revealed that staff find the characteristics related to their field of work more important, which is predictable. For example, ‘Ease of operational use’ was the most important factor for the deck personnel while ‘Easy maintenance’ was the most important factor for the engine personnel. Deck personnel rated 'ease of operational use' with 5 and above constitute 87.5% of the total, while personnel rated with 7 and 8 constitute 70.8% of the deck department (Fig. 3). The engine personnel who rated this property with 5 and above also constitutes 81% of the total. However, when Fig. 4 is examined, it is seen that 100% of the engine personnel rated ‘Easy maintenance’ with 5 and above, with 57.7% ranking 7 and 8, while 79.3% of deck personnel rated 5 and above.

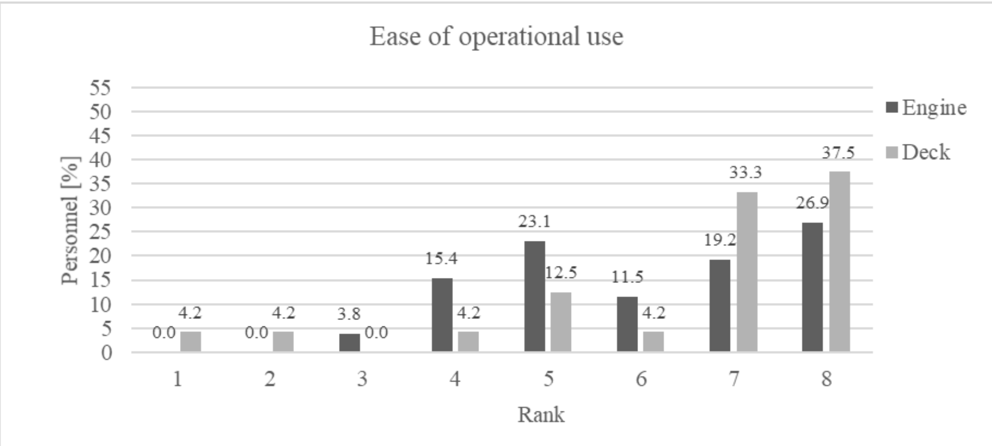

Fig. 3 The ranking of the factor ‘Ease of operational use’

On the other hand, although the property ‘Rare alarms and malfunctions’ was in the second place of importance for the personnel of both departments, 92% of the personnel of both departments ranked this property with 5 and above and 50% of deck department and 57% of the engine department ranked this factor with 7 and 8 (Fig. 5).

The property ‘No use of chemicals’ follows the properties mentioned formerly and took 4th place for both departments. The personnel who rated this factor with 5 and above constituted 70% of the engine department and 63% the of deck department Fig. 6.

When the factors rated as 4 or less important by the majority of the personnel of both departments were examined, it was seen that these factors were evaluated according to the field of duty of the personnel, as can be expected. The engine departments ranked the order of importance of ‘Small footprint and simplicity of equipment’ with 5th place, while it was the least important factor for the deck department as it was already outside the area of responsibility of deck personnel (Fig. 7). On the other hand ‘Convenience of routine checks during operation’ was the 5th place for the deck department and 6th place for the engine department (Fig. 8).

Fig. 4 The ranking of the factor ‘Easy maintenance’

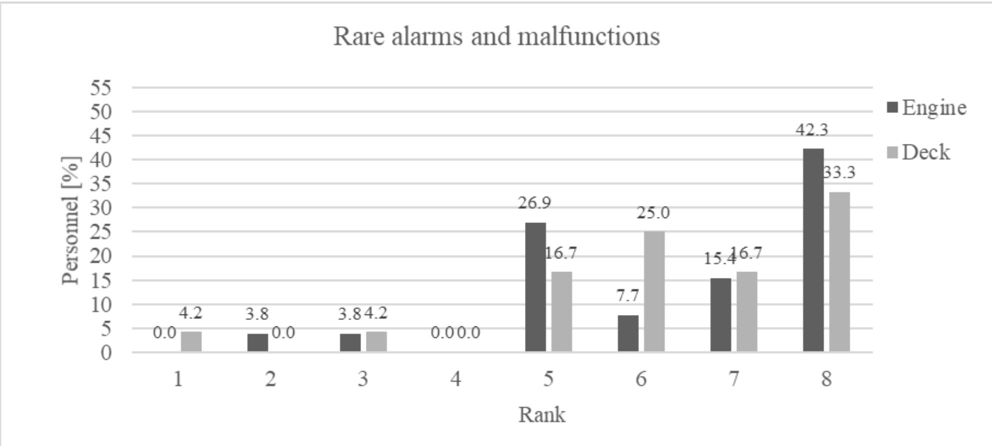

Fig. 5 The ranking of the factor ‘Rare alarms and malfunctions’

The factor ‘No requirement for preparation before ballasting’ took the 7th place in the order of importance for both departments; however, it is noteworthy that 53% of engine personnel agreed with this rank (Fig. 9). The factor ‘Requirement for little training before use’ took the last place for engine personnel (with 50% of personnel ranking it with 1) while it was on the properties and took the 6th place for deck personnel (Fig. 10).

Fig. 11 shows the arithmetic mean of the total score that each property received from all participants. The responses to the first section (Fig. 11) revealed the importance of the frequency of alarms and failures of the system. The ship's officer responsible for the loading or unloading operations of the cargo wants everything to go smoothly in these operations that may take days. On the other hand, although the preparation before ballasting is adding extra workload, it is at the bottom of the importance order.

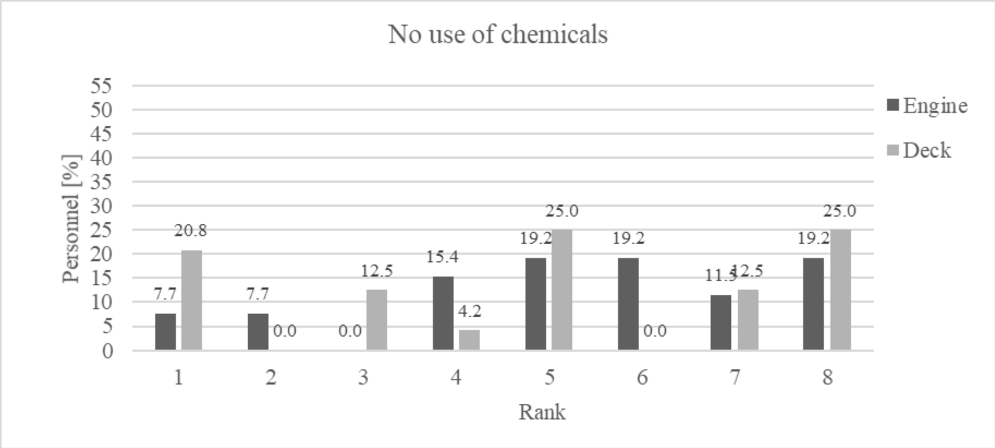

Fig. 6 The ranking of the factor 'No use of chemicals'

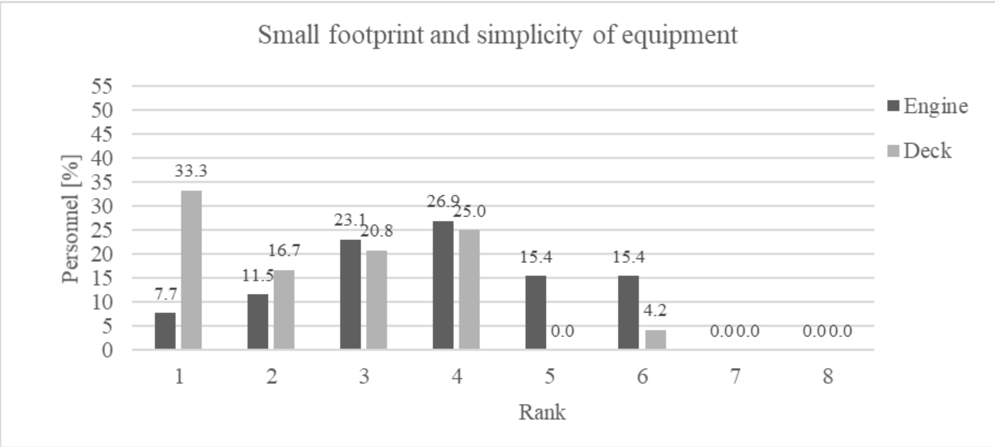

Fig. 7 The ranking of the factor 'Small footprint and simplicity of equipment'

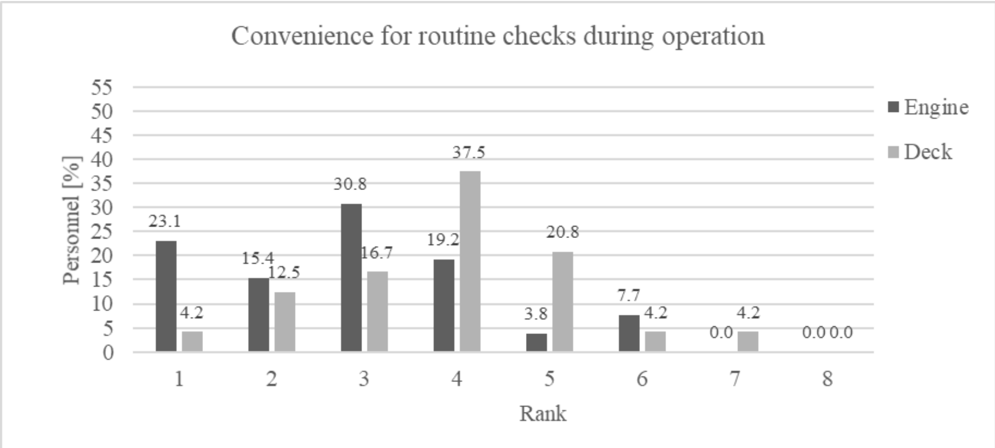

Fig. 8 The ranking of the factor 'Convenience of routine checks during operation'

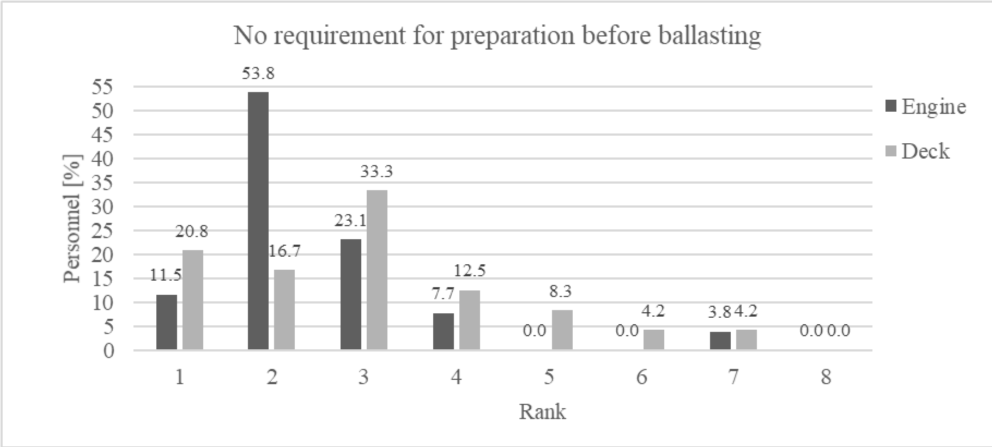

Fig. 9 The ranking of the factor 'No requirement for preparation before ballasting'

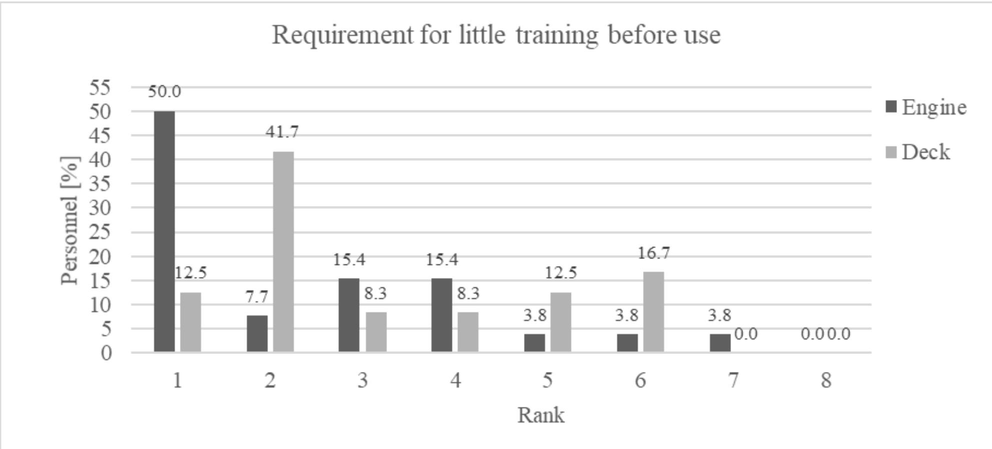

Fig. 10 The ranking of the factor 'Requirement for little training before use'

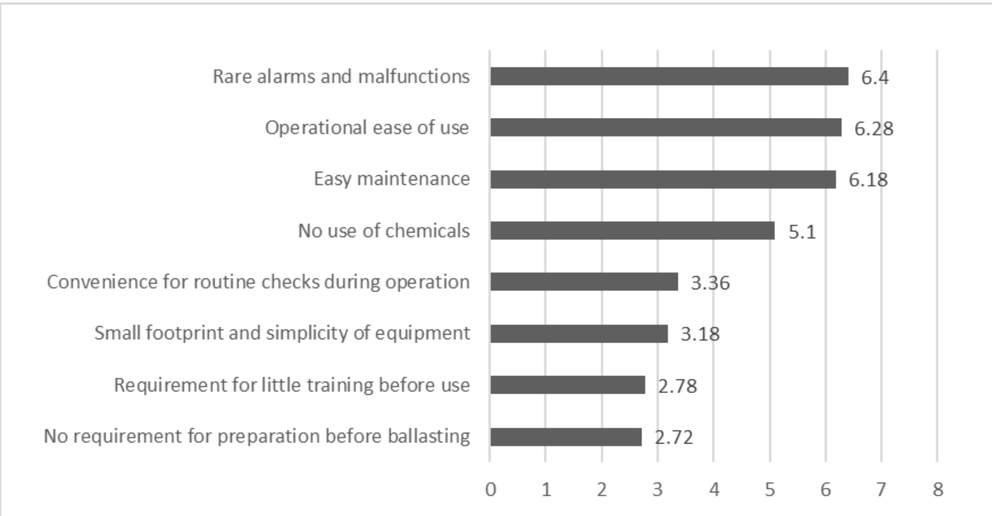

Fig. 11 Order of importance of the properties of an ideal BWTS

In the second section of the questionnaire, eight attributes were prepared in line with the properties identified for the 'ideal system' in the first stage. To assess the types of BWTS, seafarers were asked to rate the statement referring to each attribute on a five-point scale (i.e., 5 points for 'strongly agree' and 1 point for 'strongly disagree'). These attributes were presented in the questionnaire separately for El-Chem and UV systems. Each system was asked to be evaluated only by people with experience working with the particular system type. Among the 50 participants, 42 evaluated UV systems and 43 evaluated El-Chem systems.

The answers to the property associated with 'rare alarms and malfunctions,' which is seen as the most important among the identified properties, showed that the UV system was perceived as better than the El-Chem system by far in this regard (Fig. 12); total of 42.9% of respondents (4.8% of respondents strongly agree) agreed that 'UV-type BWTS rarely alarms and has rare malfunction', while 76.7% (46.5% of respondents strongly disagree) disagreed with this statement in the case of El-Chem systems. In the case of UV-type BWTS, 40.5% of respondents hold a neutral position.

The answers to the property associated with 'Ease of operational use,' which is the second in the importance list of identified properties, showed that the UV system was perceived as easy for operational use by most of the respondents (Fig. 13). Among all respondents, 50% agreed that the 'UV-type BWTS was easy for operational use' while 28.6% strongly agreed and 19% hold a neutral position. When this factor was evaluated for El-Chem systems, 32.6% disagreed (with 16.3% strongly disagreeing) that 'El-Chem type BWTS was easy for operational use' and 48.8% hold a neutral position.

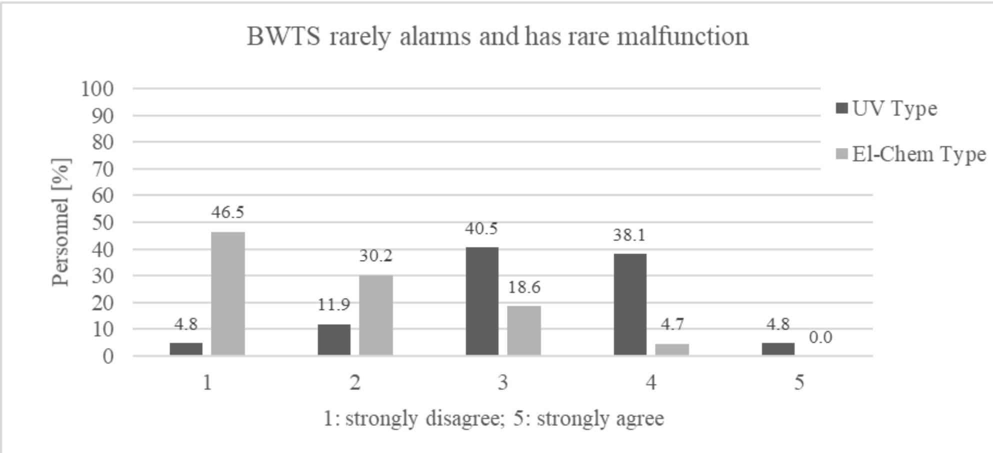

Fig. 12 Perception of systems according to the factor 'Rare alarms and malfunctions'

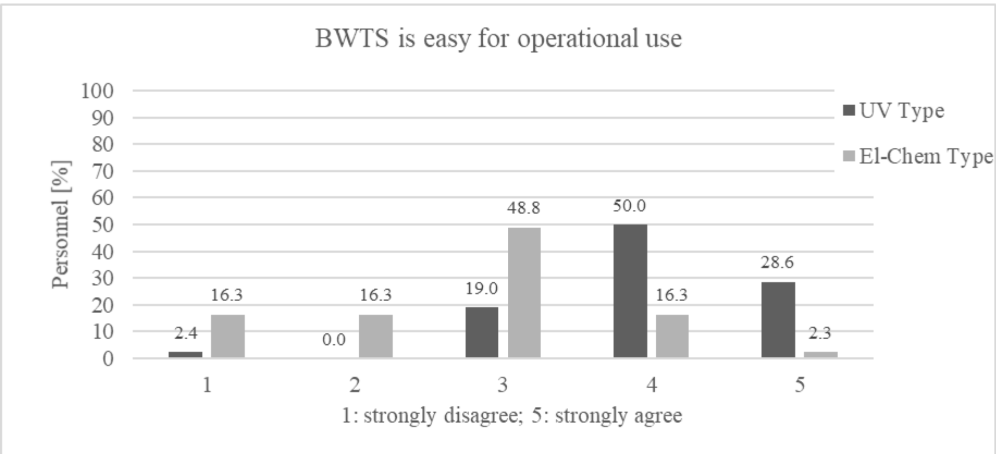

Fig. 13 Perception of systems according to the factor 'Ease of operational use'

In the importance list of properties of 'ideal BWTS,' the factor 'ease of maintenance' held the third position from the top. The respondents agreed that UV-type BWTS were easy to maintain (a total of 69% agreeing, among all respondents 11.9% strongly agree). However, 60.5% of respondents disagreed that El-Chem type BWTS was easy to maintain, while 16.3%

of respondents strongly disagreed (Fig. 14). When it comes to the 'no use of chemicals' factor, we see that respondents evaluated UV and El-Chem systems at two different extremes (Fig. 15).

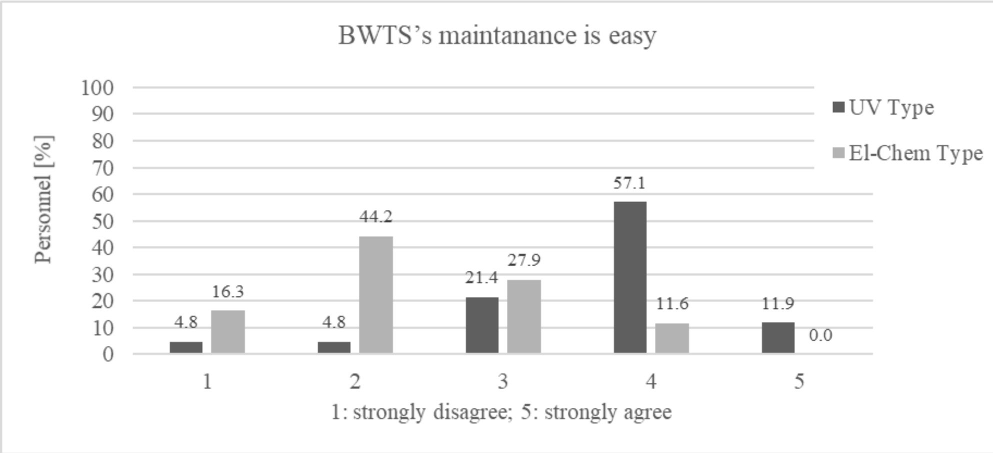

Fig. 14 Perception of systems according to the factor 'Easy maintenance'

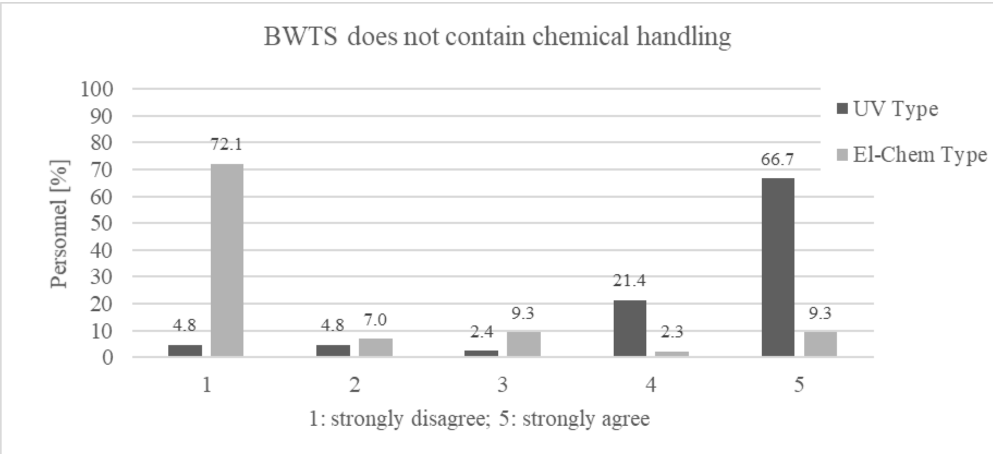

Fig. 15 Perception of systems according to the factor 'No use of chemicals'

On the other hand, although both systems did not use external chemicals for disinfection, TRO neutralization in the El-Chem system required using chemicals and both systems needed to use chemicals for maintenance. That was the reason why some respondents disagreed that 'UV-type BWTS does not contain chemical handling' while many of them disagreed 'El-Chem type BWTS does not contain chemical handling.'

El-Chem type BWTSs consisted of more components than UV-type BWTSs. The placement of this equipment (e.g., electrochemical generators, neutralization units, and TRO and sensors) in different parts of the ship, sometimes even on different floors, made routine controls difficult. This is also reflected in the survey results, where 58.1% of respondents disagree that 'El-Chem type BWTS's routine controls are easy during operation' and 'El-Chem type BWTS has a small footprint and simplicity of equipment', whereas the respondents mostly agree regarding these factors in the case of the UV-type system (Fig. 16 and Fig. 17).

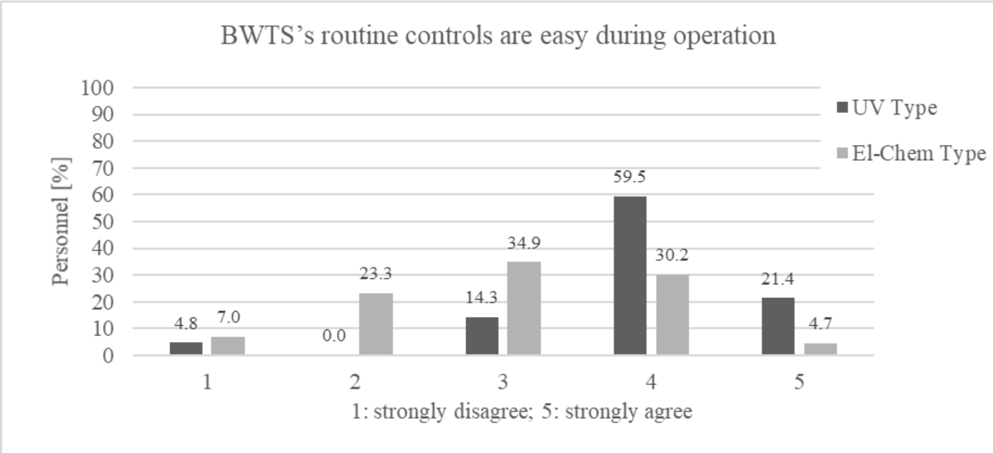

Fig. 16 Perception of systems according to the factor 'Convenience for routine checks during operation'

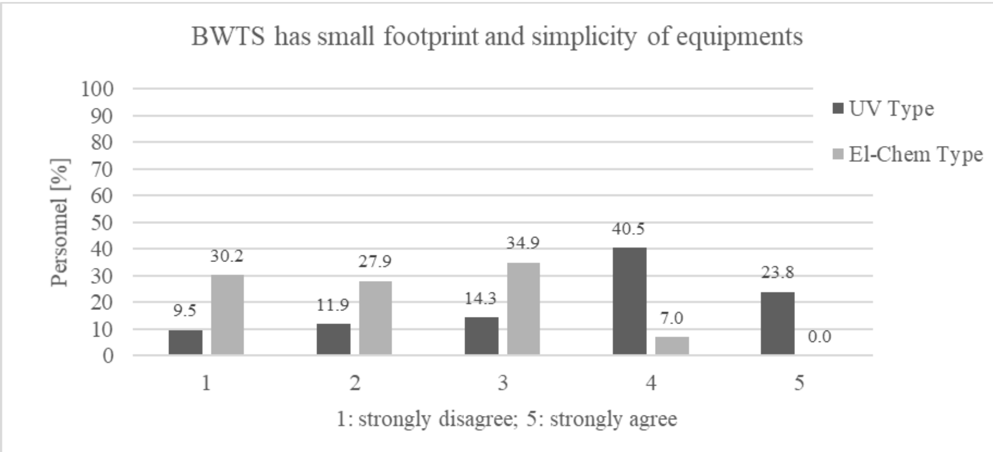

Fig. 17 Perception of systems according to the factor 'Small footprint and simplicity of equipment'

The responses regarding the factor 'Requirement for little training before use' revealed that UV-type system needed less training before use on board while El-Chem type systems require more training (Fig. 18). These responses were predictable given the training status of the seafarer and the complexity of the El-Chem system (this includes multiple pieces of equipment of the system itself and applications on board). For example, for the system to provide the correct dosage for TRO neutralization, seafarer involvement was required to adjust the chemical level in the dosing tank. When it comes to the last factor on the importance list of properties, which is 'No requirement for preparation before ballasting,' the respondents mostly (a total of 66.6% participants) agreed that 'UV-type BWTS does not need preparation before the ballast operation' while many of the participants (total of 65.2%) disagreed 'El-Chem type BWTS does not need preparation before the ballast operation' (Fig. 19).

The arithmetic mean of the total score that each BWTS type received from all participants for the factors is given in Fig. 20. This figure shows that UV systems were rated above 3 points in almost every characteristic. Fig. 20 reveals that the strongest feature of UV systems was operational ease of use, while the weakest feature was footprint and equipment simplicity. On the other hand, El-Chem systems scored less than 3 points for all of the features. The highest score was given for the 'ease of routine controls during the operation', while the lowest score was given for 'chemical handling'.

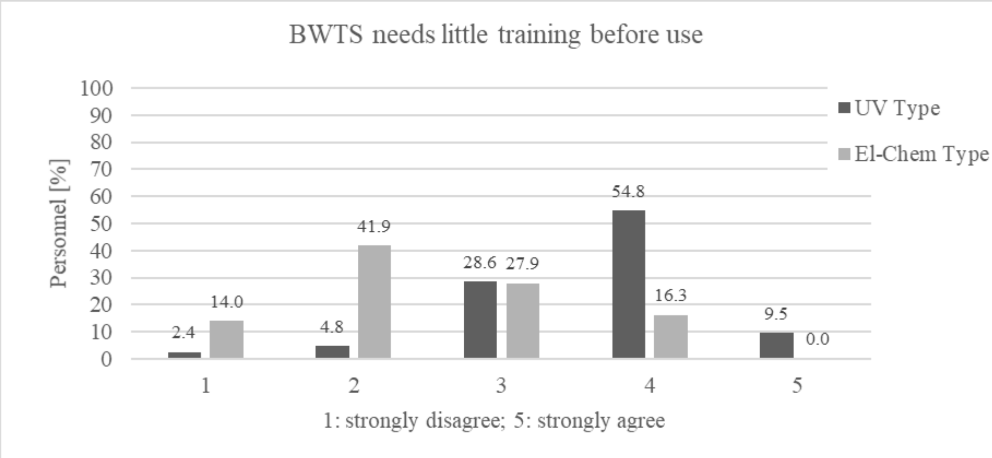

Fig. 18 Perception of systems according to the factor 'Requirement for little training before use'

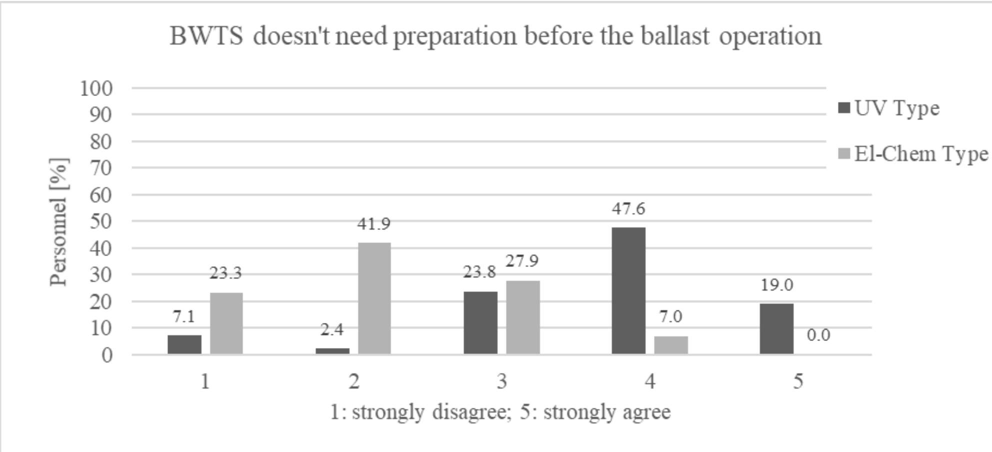

Fig. 19 Perception of systems according to the factor 'No requirement for preparation before ballasting'

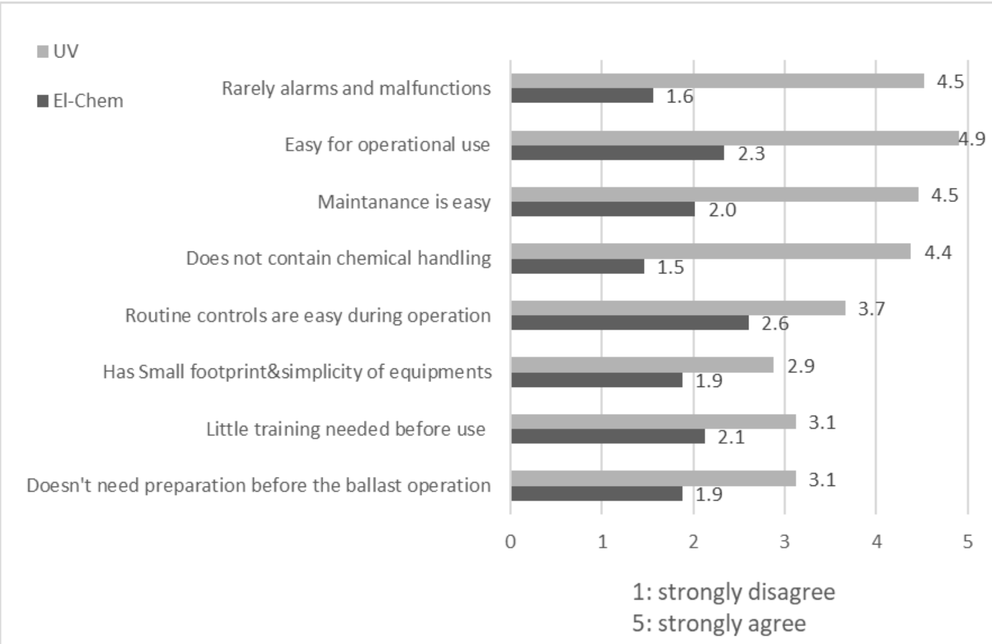

Fig. 20 Comparison of BWTS types in terms of their features

In addition to two main sections, the questionnaire also asked, ‘Which type of BWTS do you prefer’ to see the direct decision for BWTS type of the seafarers. Fig. 21 gives the choices of personnel who have experience with both types of systems.

This figure shows that while 69% of the total personnel (experienced with both types) preferred to work with the UV system, only 9.1% preferred to work with El-Chem and 21.2% stated that it was not important which system to work with. On the other hand, when the preferences of the engine department personnel were analyzed, it was seen that UV preference was in the lead with 83.3%, the rate of personnel who state that it was not important which system they would work with is 11.1%, and the rate of personnel who preferred El-Chem is only 5.6%.

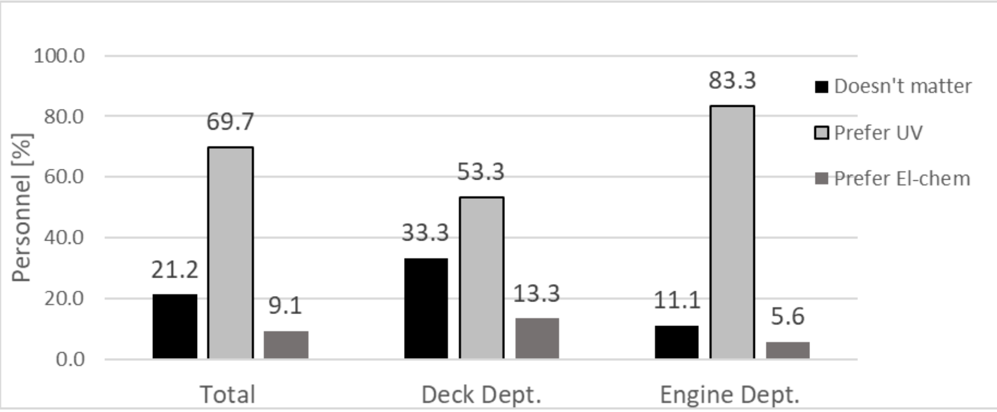

Fig. 21 The choice of seafarers with experience with both UV and El-Chem type BWTS

3.3 The Evaluation of BWTS Types with the AHP Method

3.3.1 Constructing the criteria set

The criteria set is constructed upon the property list of the ‘ideal BWTS’ determined at the end of the first phase. Among these eight properties, some of them were close to each other. The ‘need for little training’ is related to ‘ease of use,’ and the small footprint of the BWTS also makes it easy for routine checks. Therefore, to obtain more realistic results, the four properties were combined in pairs to form two criteria for the AHP technique application. As a result, six criteria were identified based on the responses to the questionnaire, failure reports, and the results obtained from bilateral interviews. These six criteria and their associated rationales are listed below.

Criterion 1- Operational ease of use and fewer training requirements before use: Ships are complex structures with many different systems working together. New personnel joining these complex structures may encounter different brands and types of equipment performing the same task for the first time. For using some equipment, personnel may need to be trained beforehand. It is a great advantage for the personnel on board that the operational use of the BWTS to be selected is easy for the ship's officers and requires very little training before use. It should also be taken into account that ballast water treatment on board may not meet compliance standards due to inadequate training on the BWTS installed [45,55].

Criterion 2- No chemical handling requirement: In El-Chem systems, a chemical agent (sodium bisulfite) is dosed to inactivate residual oxidants in the ballast water during the deballasting process. It is important to take the necessary safety precautions for these chemicals and to ventilate the area where they will be stored. To store and use this neutralizing chemical on board, the ship's personnel must first be given the necessary training. Some brands of UV systems also use chemical liquid to clean the UV reactor. This chemical liquid must be stored in designated chemical storage areas on-board ships. During the filling of this chemical liquid into the reactor cleaning unit, ship personnel must take special protective measures. Since the ship's crew will inevitably be in close contact during the transportation and handling of chemicals, the crew has a negative view of the systems using these types of chemicals.

Criterion 3- Rare alarms and malfunctions: Usually, ballast and deballast operations take place during cargo loading or unloading. The ship's officer in charge of loading or unloading cargo wants everything to run smoothly during these operations, which can take days. Frequent malfunctions or sounding of the alarm in some BWTSs affect the ship's operations and also distract the ship's officer. The most critical failure mode, especially in tanker ships, is the non-synchronization of cargo and ballast operations, which should occur simultaneously [56]. For example, a chief officer working on a tanker ship may also need to fill the cargo tanks to 98% capacity. To achieve this critical loading capacity, he has to give his full attention to the level of the cargo tanks. On the other hand, there may also be a need for ballast discharge simultaneously. An alarm that may sound in the BWTS may distract the chief officer and cause him to misoperate.

Criterion 4- No preparation requirement before ballast operation: Before ballast and deballast operation, some BWTSs experience jams in air-operated or electrically operated valves. The main cause of the jamming of air-operated valves is moisture in the air. For this reason, the water in the air must be drained before the BWTS is commenced. Once the air has been drained, it may be necessary to open and close the valves before the operation for control purposes.

Especially on long voyage ships, sodium bisulfite chemical precipitates and solidifies both in the automatic neutralization unit and in the circuits of the unit. As a result of solidification at the inlets of the solenoid valves, chemical passage through the valves is prevented and the TRO sensor is alarmed. On long-voyage ships, solenoid valves should be checked and cleaned if necessary before operating the BWTS. In addition, if solidification is detected in the automatic neutralization unit, it should be remixed with water. In addition, the amount of neutralization agent (sodium bisulfite) in the automatic neutralization unit should be checked before deballasting. If it is not sufficient, it should be supplemented and mixed with water.

The mechanical filter in the first stage in both El-Chem and UV-type systems should be cleaned regularly by ship personnel.

Criterion 5- Easy maintenance: Since BWTSs are generally used in cargo loading or unloading operations, in the event of a malfunction, the malfunction needs to be fixed within a limited time so that the cargo operation is not affected. This creates stress for the engine officers responsible for the maintenance of the ship. The ease of maintenance of the BWTS before or in the event of failure is a great advantage, especially for engine officers.

Criterion 6- Small footprint of the system and easy routine controls: It is an important disadvantage that the equipment that makes up the system is far from each other. Especially in retrofit ships, different equipment of some BWTSs is located on various floors and compartments due to space constraints. In the event of a breakdown or during routine inspections, there is a severe loss of time as they are located in very different places. The large size of the equipment also makes maintenance difficult.

3.3.2 The application of AHP for evaluation of BWTSs

The pairwise comparison matrices were built upon basically the survey responses to each criterion. The total scores obtained for the criteria according to the survey results are given in Table 4.

Table 4 The total score received by the criteria

Criteria	Total Score
C1: Operational ease of use and fewer training requirements before use	227
C2: No chemical handling requirement	255
C3: Rare alarms and malfunctions:	320
C4: No preparation requirement before ballast operation	136
C5: Easy maintenance	309
C6: Small footprint of the system and easy routine controls	163

To use Saaty's Fundamental scale, the ratios of the criteria scores to each other were utilized (Table 5), and based on the importance levels, a pairwise comparison matrix was formed (Table 6).

Table 5 Importance values corresponding to criterion ratio

Criterion ratio	Importance values
1.00-1.15	2
1.15-1.30	3
1.30-1.45	4
1.45-1.60	5
1.60-1.75	6
1.75-1.90	7
1.90-2.10	8
2.10-2.36	9

Table 6 Pairwise comparison matrix between criteria

Criteria	C1	C2	C3	C4	C5	C6
C1: Operational ease of use and less training required before use	1.000	0.500	0.250	6.000	0.250	4.000
C2: No chemical handling requirement	2.000	1.000	0.333	7.000	0.333	5.000
C3: Rare alarms and malfunctions	4.000	3.000	1.000	9.000	2.000	8.000
C4: No preparation requirement before ballast operation	0.167	0.143	0.111	1.000	0.111	0.333
C5: Easy maintenance	4.000	3.000	0.500	9.000	1.000	7.000
C6: Small footprint of the system and easy routine controls	0.250	0.200	0.125	3.000	0.143	1.000
Column Total	11.417	7.843	2.319	35.000	3.837	25.333

Relative importance levels of criteria (Table 7) were calculated based on the normalized pairwise comparison of the criteria.Table 7 shows that the most effective criterion is ‘rare alarms and malfunctions.’ This criterion is followed by ‘easy maintenance.’ The importance of the criteria ‘no preparation requirement before ballast operation’ and ‘small footprint of the system and easy routine controls’ were very low compared to others.

Table 7 Relative importance levels of criteria

Criteria	Importance levels
C1: Operational ease of use and fewer training requirements before use	0.1089
C2: No chemical handling requirement	0.1551
C3: Rare alarms and malfunctions:	0.3764
C4: No preparation requirement before ballast operation	0.0252
C5: Easy maintenance	0.2904
C6: Small footprint of the system and easy routine controls	0.0440

The priorities matrix was formed (Table 8) and the consistency ratio for criteria was calculated (Table 9). Since the CR value was less than ≤ 0.10, the determined pairwise comparison matrix was consistent, so the pairwise comparisons of El-Chem and UV-type BWTSs were conducted according to responses given to the questionnaire (Fig. 20). The average scores of both BWTSs from the questionnaire and the ratio of the score of UV to El-Chem systems for each criterion are shown in Table 10.

Table 8 Priorities matrix

Criterions	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5	Criteria 6
Criteria 1	0.088	0.064	0.108	0.171	0.065	0.158
Criteria 2	0.175	0.128	0.144	0.200	0.087	0.197
Criteria 3	0.350	0.383	0.431	0.257	0.521	0.316
Criteria 4	0.015	0.018	0.048	0.029	0.029	0.013
Criteria 5	0.350	0.383	0.216	0.257	0.261	0.276
Criteria 6	0.022	0.026	0.054	0.086	0.037	0.039

Table 9 Calculating the consistency ratio for the criteria

Criterions	Row total	Importance levels	Row total/Importance levels
Criteria 1	0.6804	0.1089	6.245899
Criteria 2	0.9916	0.1551	6.393211
Criteria 3	2.4370	0.3764	6.475107
Criteria 4	0.1543	0.0252	6.114188
Criteria 5	1.9144	0.2904	6.591922
Criteria 6	0.2664	0.0440	6.062173
λ= 6.313750	**CI= 0.062750**		**CR= 0.050605**

Table 10 Scores of UV and El-Chem systems according to the survey results

Criterions	El-Chem	UV	**Ratio**
Operational ease of use and fewer training requirementsbefore use	2.595	3.830	**1.476**
No chemical handling requirement	1.700	4.400	**2.588**
Rare alarms and malfunctions	1.810	3.26	**1.801**
No preparation requirementbefore ballast operation	2.190	3.69	**1.685**
Easy maintenance	2.350	3.67	**1.562**
Small footprint of the system and easy routine controls	2.605	3.75	**1.44**

Finally, the pairwise comparison of the UV and El-Chem alternatives was made. This AHP application, mainly based on a survey of expert seafarers, showed that UV systems were 1.76 times more preferred than El-Chem systems based on the experience of expert seafarers

4. Conclusion and Discussion

In the first phase of this study, to determine the properties that an 'ideal BWTS' should have, expert seafarers of the maritime company were interviewed. In addition, the failure reports written about the BWTSs of the maritime company, which integrated the El-Chem system in 2015, the UV-1 system in 2019, and the UV-2 systems in 2021 into its ships in its fleet, were examined. As a result of the bilateral interviews and failure report examination, eight properties of an ideal system were determined. It was observed that using chemicals, alarm and malfunction situations, and the need for preliminary preparation for the operation were among the properties that made the system difficult to be preferred to work with. On the other hand, the ease of use and maintenance of the system, the fact that the system contains few components and takes up little space in total, the ease of routine checks, and the fact that it requires less training before use are among the prominent properties for the systems to be preferred by seafarers.

After the first phase of this study, seafarers were asked to prioritize these characteristics through an online survey, as each seafarer's priorities might be different. In the questionnaire, the seafarers were also asked to evaluate the UV and El-Chem systems according to the features determined. The general approach of the staff of each department was to prioritize the aspect of the ideal system that interested them, i.e., 'Ease of operational use' is the most important factor for the deck personnel while 'Easy maintenance' is the most important factor for the engine personnel. On the other hand, it is seen that the least important feature for the engine department is the 'Requirement for little training before use' for the engine department, while for the deck department, it is 'Small footprint and simplicity of equipment.

In the third phase of this study, the AHP method was utilized to have a common perspective of the seafarers' evaluation of these systems. The eight properties of the 'ideal BWTS' were identified into six criteria as some properties have addressed similar issues. For the AHP method, each personnel's evaluation was weighted the same and the questionnaire scores were employed. The criteria from most important to least were as follows:

- Rare alarms and malfunctions
- Easy maintenance
- No chemical handling requirement
- Operational ease of use and fewer training requirements before use
- Small footprint of the system and easy routine controls
- No preparation requirement before ballast operation

This set of criteria shows that 'Rare alarms and malfunctions' is the most important criterion from the perspective of all seafarers. Ballast and deballast operations, which usually take place during cargo loading or unloading, can last for days. It is of great importance for seafarers that everything runs smoothly during these operations. Frequent malfunctions or alarms in some BWTSs not only affect the ship's operations but also distract the chief officer. Especially in tanker ships, the ship's officer should give his full attention to the level of cargo tanks in operations where critical loading capacity must be reached. On the other hand, simultaneous ballast discharge may also be required. An alarm that may sound in the BWTS may distract the chief officer and cause him to work incorrectly.

According to the pairwise comparison of UV and El-Chem alternatives, UV-type BWTS is 1.76 times more preferable than the El-Chem type BWTS as a common approach. The study showed that the strongest feature of UV systems from seafarers' perspective is the operational ease of use, while the weakest feature is size and equipment simplicity. The size of the system is a problem in terms of maintenance especially when UV lamps are needed to be replaced. On the other hand, the El-Chem systems have been rated below the average for all features determined. The highest score was given for the ease of routine controls during the operation, while the lowest score was given for chemical handling. Although El-Chem systems produce disinfection chemicals on board, extra chemicals are still needed for both TRO control and system maintenance, and chemical use may be the most significant disadvantage of El-Chem type BWTSs for seafarers. Because chemical handling is always seen as a risk by seafarers no matter what the '*chemical*' is. Despite the presence of all personal protective equipment on board in case of chemical handling, seafarers react negatively to using chemicals. In addition, El-Chem type BWTSs are more complex system than UV systems. Therefore, maintenance of El-Chem type BWTSs is more difficult for ship personnel.

It should be noted that this study is concluded depending on the experience of the seafarers currently working for one maritime company. However, their experience is not limited to the three brands of BWTSs installed on the ships of this company. Totally 50 expert seafarers have contributed to the evaluation and total of 10 different brands is reported to be experienced, and 33 of the respondents have experience in both UV and El-Chem systems.

BWTSs have been used extensively, especially in the last six years. Maritime companies consider some specified criteria in the BWTS selection process. There are certainly several parameters related to technical issues, such as operational and navigational characteristics of the vessels, and costs. This study aims to contribute to the evaluation and decision-making processes by including the perspectives and experiences of the seafarers who will operate the systems after they are installed on board the ships. The six criteria that were determined and prioritized in this study can be used both in determining the technologies to be included in the system to be adapted to the ship and in brand-related evaluations when determining the appropriate brand. When deciding on ballast water treatment systems where millions of dollars of investments will be made, user experiences with the systems on the market can be evaluated by considering these criteria determined directly by the evaluations of seafarers.

In today's maritime market, there are many BWTSs with IMO Type Approval and USCG Approval under different brands and types. Shipowners should pay attention to the qualitative criteria of the equipment as well as the installation and operating costs during the BWTS selection phase. The systems using even the same methods (i.e., UV, El-Chem, or any other.) may perform differently in real conditions, especially in ports with challenging water conditions where requirements of IMO and USCG are exceeded. When TSS content exceeds the physical limits of the systems, blockages, and failures are inevitable. The maritime company subject to this study uses two different brands of UV systems on its four ships. While the filter mesh size of the low-cost system is 50 μm, the filter mesh size of the other is 20 μm. However, BWTS with a smaller mesh size filter has a pump that increases its back flushing performance. According to the observation of seafarers, although the filter mesh is smaller, fewer clogging problems are encountered with this second BWTS. Seafarers relate this to the performance of the back flushing. However, it should be noted that as there are no systematic reports on filter clogging, this assessment of the seafarers is based on their perceptions.

It is important to include an assessment of ship experience in the selection parameters to ensure that the systems can be operated smoothly (or with as few problems as possible) in accordance with the rules. The frequency and magnitude of problems encountered during using the systems may push seafarers outside the rules (i.e., bypassing the system) to reduce time and expectable economic losses related to lost time. In such a case, in addition to the penalties and fines that may be imposed, situations that could result in the blacklisting of the vessel could result in more significant future economic costs for shipowners, while undermining all efforts to eradicate harmful and non-native species.

This study is limited to the views of the seafarers accessed and their experiences with the two types of BWTS. As the experience development progresses, further studies of this kind will allow for more comprehensive assessments and more effective use of experience in decision-making.

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