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Investigation of Ballast Water Treatment System Selection Parameters and Cost Analysis: Tanker Ship Application

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ABSTRACT

Ballast water is taken into the tanks of ships to ensure stability during voyages, but it also contributes to the spread of invasive species, causing ecological and economic damage. To address this problem, the International Convention for the Control and Management of Ships' Ballast Water and Sediments was introduced in 2017, which sets D2 standards to regulate the number and size of organisms in ballast water. The aim of this study is to identify the key factors in the selection of a ballast water treatment system and to calculate the costs associated with a tanker ship. Through a literature review, important parameters affecting the selection of ballast water treatment systems were identified. Based on these parameters, the most suitable system for a chemical tanker was determined and a cost analysis was performed. The study specifically focused on the hydrocyclone UV ballast water treatment system and evaluated both installation and operating costs. The findings show that the hydrocyclone UV system is the most suitable option for chemical tankers in accordance with international regulations. The research emphasises that the initial installation cost as well as operating costs should be considered in the decision-making process. The results provide valuable information to shipowners and operators in selecting an efficient and cost-effective ballast water treatment system that meets regulatory requirements.

Keywords: Ballast water, ballast water management, tanker ship, cost analysis

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Balast Suyu Arıtma Sistemi Seçim Parametrelerinin İncelenmesi ve Maliyet Analizi: Tanker Gemisi Uygulaması

ÖZ

Balast suyu, seferler sırasında dengeyi sağlamak için gemilerin tanklarına alınır, ancak aynı zamanda istilacı türlerin yayılmasına katkıda bulunarak ekolojik ve ekonomik zarara neden olur. Bu sorunu ele almak için, balast suyundaki organizmaların sayısını ve boyutunu düzenlemek için D2 standartlarını belirleyen Gemilerin Balast Suyu ve Sedimanlarının Kontrolü ve Yönetimi için Uluslararası Sözleşme 2017 yılında uygulamaya konmuştur. Bu çalışmanın amacı, bir balast suyu arıtma sisteminin seçimindeki temel faktörleri belirlemek ve bir tanker gemisi ile ilgili maliyetleri hesaplamaktır. Literatür taraması yoluyla, balast suyu arıtma sistemlerinin seçimini etkileyen önemli parametreler belirlenmiştir. Bu parametrelere dayanarak, bir kimyasal tanker için en uygun sistem belirlenmiş ve bir maliyet analizi yapılmıştır. Çalışma özellikle hidrosiklon UV balast suyu arıtma sistemine odaklanmış ve hem kurulum hem de işletme maliyetlerini değerlendirmiştir. Bulgular, hidrosiklon UV sisteminin kimyasal tankerler için uluslararası yönetmeliklere uygun en uygun seçenek olduğunu göstermektedir. Araştırma, karar verme sürecinde ilk kurulum maliyetinin yanı sıra işletme giderlerinin de göz önünde bulundurulması gerektiğini vurgulamaktadır. Sonuçlar, mevzuat gerekliliklerini karşılayan verimli ve uygun maliyetli bir balast suyu arıtma sistemi seçme konusunda armatörlere ve operatörlere değerli bilgiler sağlamaktadır.

Anahtar Kelimeler: Balast suyu, balast suyu yönetimi, tanker gemisi, maliyet analizi

1 Introduction

Transportation is carried out by sea, air, road, rail, and pipelines (Battal Sal & Cubuk, 2022). Maritime transport has the largest share, with 90% of the transportation in the world (Özbay et al., 2024). This transportation is carried out by ships (Vural & Yonsel, 2015). Loading and unloading operations on ships require stability calculations. The main objective of ship owners is to sail the ship at full capacity. However, this is not always possible. Ships can depart from the port either without any cargo or with a small amount of cargo, without being loaded at full capacity. In cases where ships sail with no cargo or with little cargo, the ships receive ballast (which means additional cargo, i.e., sea water). This sea water is carried in tanks called "ballast tanks". There are many kinds of living organisms in ballast tanks, which are transported through the tanks (Sanlıer, 2019).

To ensure stability control, ships take in sea water, called ballast water, when they are not loaded. Because of ballast water, the stress on the ship structure is reduced, and the propeller is allowed to sink into the water (Başhan et al., 2016). When organisms are released in the ballast water into another ecosystem, this may disrupt the ecological balance. Species brought with ballast water can become invasive in their new environment. In addition, they cause economic losses. To prevent these problems, the Ballast Water Management (BWM) Convention was published by the (IMO) in 2004 and entered into force on September 8, 2017. After the entry into force of the BWM, ships are required to have a ballast water treatment system according to their gross tonnage, year of construction, and ballast capacity. 2018-2022 was a busy period for shipyards and ship owners for integrating ballast water treatment systems on board (Yonsel & Vural, 2017). It is important to select the ballast water treatment system by considering the ballast capacity of the ship and the key parameters of efficiency and utility.

Approximately 10 million tons of ballast water are transported from one location to another globally every year. Daily 7000 invasive species inhabit this ballast water. These invasive species pose a threat to human, animal and plant life (Satir, 2014). These organisms are large enough to pass through the ballast water system and pumps and have a wide range of sizes. Of the organisms that enter the ballast tank, those that remain alive during their voyage can harm the new ecosystem they reach (Elcicek & Çakmakci, 2016). When these harmful aquatic organisms reside in new ecosystems, they disrupt the order of the food chain. After reproduction, these species can become invasive. These invasive species also disrupt the coastal economy by damaging fishing grounds. Apart from the economic impact, harmful viral pathogens and bacteria, such as Vibrio cholerae and E. Coli, which harm human and environmental health, can also be carried with ballast water (Güney, 2011).

As problems arising from ballast water have reached a serious level, the International Maritime Organization (IMO) initiated studies on this issue. On February 13, 2004, at the conference held by the IMO in London, BWM was completed and submitted for signature. For this convention to enter into force, ratification by 30 countries representing 35% of the world merchant fleet is required (Vural & Yonsel, 2015). On September 8, 2016, this condition was met, and the convention entered into force on September 8, 2017 (Bilgin Güney, 2018).

IMO BWM consists of 5 parts. The components include general provisions, standards for BWM, and control requirements for ships, special area requirements, and the measurement and certification of ballast water methods. The ballast water treatment rules are included in the section on standards for BWM (International Maritime Organization , 2017). The ballast water treatment sections are classified according to D1 and D2 standards. In the D1 standards, a ship is required to change the ballast water before entering the port (Tokus, 2019). In the D1 standards, the ship should empty the ballast water without using any augmentation system and replace it with fresh ballast water from the open sea. This method should be performed at a distance of 200 nautical miles from land and at a depth of 200 meters. The volume change should be 95%. Another method is the overflow method. In the flooding method, at least 3 times the volume of the ballast water in the tank should be replaced. The volumetric change must be 95%. In the D2 standards, if the size of the organisms in the ballast water is equal to or greater than 50 µm per cubic meter, the concentration must be less than 10 organisms per cubic meter. If the size of the organisms is less than 50 µm and greater than or equal to 10 µm , there should be fewer than 10 organisms per millilitre (Vural & Yonsel, 2015). According to IMO guidelines, D2 standards are required for ships as per BWM. To meet these standards, ballast water treatment systems have been developed using mechanical, physical and chemical methods (Tokus, 2019).

2 Literature Review

In the literature, there are various studies on ballast water treatment systems. Various treatment system techniques create alternatives for ship owners. The high costs of such technologies also increase freight rates. Other methods of cleaning the ballast water should be considered, considering the costs of the chemicals used in the treatment and their environmental impact. Research should also be carried out on methods to clean ballast water at the shore. The most suitable system is one in which different methods are used together economically (Balajt & Yaakob, 2011).

Ballast water discharge rules vary according to the IMO and the United States Coast Guard (USCG). According to the USCG, if ballast water is to be discharged into the sea, certain requirements must be fulfilled. These are: there should be less than 1 aquatic organisms in 100 m^3, there should be less than 1 viable aquatic organisms in 100 ml, there should be less than 103 bacteria and less than 104 viruses in 100 ml (Albert et al., 2013)

The accumulated sludge should be cleaned from time to time because microorganisms from the sludge at the bottom of the ballast tank can cause the proliferation of microorganisms in the tank. Thanks to new ballast technologies, large volumes of ballast water can be treated by different methods such as UV (ultraviolet) light, ozone, biocide, and filtration. Ballast treatment methods vary depending on the ship type and requirements (Gonçalves & Gagnon, 2012).

There are 69 treatment systems with IMO-type approval. When IMO-approved systems are analysed, filtration methods are mostly used in pretreatment. Current technology has enabled the widespread adoption of UV systems. While 41 of these systems used a single method in the second treatment, 21 of them used more than one treatment method. If active substances are used in the system, the UV method is not included; otherwise, it is included. The electrolysis/electro chlorination method is the second most used treatment method in 17 systems. The ballast water capacities of IMO-type pumps range from 20 m3/hour to 16,000 m3/hour. The area covered by these systems is 1 m^2–12.4 m^2 for systems with a capacity of up to 500 m^3/hour and 77.6 m^2 for systems larger than 500 m^3/hour. Their height ranges from 1 to 3.9 meters. Glo En-Patrol Ballast Water Treatment System is the most widely sold system (Güney, 2017).

Every living organism has a temperature range in which it must exist. When the temperature range is exceeded, living organisms die. In the research conducted on MS Don Quijote, an attempt was made to clean ballast water using temperature. For this research, 4 starboard tanks, port tanks, and aft peak tanks of the ship with a total ballast capacity of 8075 MT were used. The water collected from these tanks was sent to a cleaning tank. Before being sent to the cleaning tank, the ballast water was passed through 50-micrometer filters. The water in the cleaning tank was heated using a steam circuit. The water in the cleaning tank was gradually heated from 55 °C to 80 °C. ballast water samples taken before heating were checked for the presence of zooplankton, plankton, and bacteria by dropping chemicals into them and their ratios were determined. After the water was sent to the heating tank, it was observed that some of the organisms in the water started to disappear at 55-60 °C. Samples taken from the tank heated to 80 °C were checked again. It was determined that 95% of the water was cleaned. However, although it met the IMO standards in terms of concentration, some plankton were larger than these standards. Although partial success was achieved in the study, the operation is difficult for ships on short voyages. In addition, the seawater temperature is important for effective treatment. Because heating the ballast water and performing the operation take time, vessels should account for this duration in their scheduling (Quilez-Badia et al., 2008).

For ships with a ballast capacity of 500-1500 m^3 / h, the most appropriate among the filtered electrolysis, filtered deoxygenation, filtered UV, and filtered chemical treatment systems was selected. Cost is an important factor in selecting ballast water treatment systems. In the expert interviews and evaluations, it was concluded that UV treatment systems with filters are the most suitable systems (Yazır & Gedik, 2022). 52,376 deadweight tonnage (DWT) and 28,930 m^3 ballast capacity of a dry cargo ship were investigated to determine the operating cost of a UV treatment system with filters. The USCG mode of the treatment system consumes more energy than the IMO mode. The fuel type used in energy-consuming generators also affects the cost. The purchase price of fuel varies by region. When the ship performs 16 ballast treatment operations per year, the operating cost ranges from at least USD 6039, to at most USD 20146, according to the variables affecting fuel expenditure and cost (Başhan & Kaya, 2022).

Tokus (2019) aimed to determine the most suitable ballast water treatment system for dry cargo ships. In the study, 15 criteria were developed based on basic technical and economic factors such as operational requirements of the ship, compliance with international standards, energy efficiency, costs, maintenance and environmental impacts. In this context, UV+filtration, electrolysis filtration and chemical filtration systems were compared. As a result of the evaluations, UV+filtration system was determined as the most suitable option in terms of low maintenance requirement, high energy efficiency and environmental sustainability. The installation, design, and 20-year maintenance costs were calculated for ship A, which had a 28,500 DWT and a 9,500 m^3 ballast capacity, and the cost was 389,300 Euros.

Ballast Water Management Convention (BWMC) has been signed by 81 countries as of January 9, 2020. Checking if the ports comply with the BWMC. In the D1 part of the Convention, control over the changes in water conditions is carried out by the port authority. However, it is not easy to understand whether the ships comply with the D2 rules or require further analysis. To ensure control of the spread of invasive species, it is obligatory to install BWTS on ships. The ballast water exchange method described in D1 could be used until 2021 for ships built before 2009. According to a Lloyds Register report in 2010, the area covered by the filtration/UV system was approximately 3.5–18 m2. The ballast water treatment system requires energy for operation. These energy requirements increase fuel costs. Operation and maintenance costs;

- Filtration + UV 20 USD/1000 m3
- Filtration + chlorine dioxide, 80 USD/1000 m3
- Filtration + sodium hypochlorite: 50 USD/1000 m3 (Eleyadath et al., 2021)

3 Ballast Water Treatment Systems

The ballast water treatment systems are integrated into the ship. The primary objective of ballast water treatment systems is to neutralize the organisms present in the water. Mechanical, physical, and chemical methods are available for ballast water treatment. These methods were implemented using various techniques. A comparison of these treatment methods is presented in Table 1. Studies have shown that using a single treatment method is not effective for ballast water treatment. In treatment systems, large organisms are primarily retained by filtration, and in the second stage, another treatment method is used (Bilgin Güney, 2018).

3.1 Mechanical Treatment

The mechanical treatment involves ballast water before it enters the ballast tank. The aim of this study is to reduce the number of organisms in ballast water. Filtering and hydrocyclone separation are more prominent in this method. With this method, large organisms that enter the ballast tank are prevented from damaging the second treatment system (Güney, 2011). The UV method applied after filtration is one of the most effective methods for treating ballast water (Gonçalves & Gagnon, 2012).

3.2 Physical Treatment

In physical treatment, organisms are attempted to be destroyed by heating ballast water. As temperature increases, the duration of its effect on organisms decreases. More energy is required for thermal treatment (Aşıkoğlu, 2014). The UV method is an effective approach for cleaning organisms. Using the UV method, the structures in the DNA, RNA, and cell proteins of the organisms are disrupted, and the organisms are inactivated. It is recommended to use the UV light after effective pre-treatment. Because crustacean organisms and life forms are highly resistant, the use of UV radiation alone may not be sufficient for treatment. With the use of a pre-treatment system, adequate treatment levels can be achieved (Güney, 2017). With ultrasound technology, the vibration generated by high-frequency energy, introduced into the liquid, has physical and chemical effects (Joyce et al., 2003). As a result, the cell walls of the organisms are destroyed by the bursting of bubbles formed in the ballast water. However, when the ultrasonic system is not used with another system, it has been observed that its success remains between 70% and 90% (Sanlıer, 2019).While cavitation has advantages such as ease of use, small footprint, and lack of added chemicals in ballast water treatment, it has disadvantages such as high operating costs and safety risks (Bilgin Güney, 2018).

3.3 Chemical Treatment

To remove organisms via chemical methods, biocides, which are chemical substances, need to be added to ballast water. Biocides ensure that the organisms in the ballast water die. To avoid the harmful effects of biocides on the environment and humans, the type of biocide to be used should be carefully selected. Biocides are stored on board in liquid or solid form (Satir, 2014). chemical methods expose ship personnel to chemicals and corrodes ballast tanks (McCluskey & Holdø, 2009). The other chemical methods used to treat ballast water are electrochlorination (electrochemical) and deoxygenation. In the deoxygenation method, aquatic organisms are deprived of oxygen and are thus killed. However, deoxygenation is not effective in organisms living in oxygen-free environments. Electrochemical systems have a lethal effect on aquatic organisms by exploiting the impact of an electrical field (Sanlıer, 2019). The disadvantage of this system is that the disinfectant is stored on the ship, occupying space and posing risks to personnel safety (Bilgin Güney, 2018). Ballast water treatment systems are given in Table 1.

Table 1: *Treatment methods and comparisons*

Treatment Type	Treatment Method	Description	Advantage	Disadvantage
Mechanical Treatment	a) Filtration	Use of discs or fixed screens	Effective for large particles	Not effective for small particles
	b) Sedimentation	Used to increase the particle size	Increased particle size	Additional water storage tank required
	c) Hydrocyclone	High-speed centrifugal force	Can be more effective than filtration	Effective for large particles
Physical Treatment	a) Ultraviolet (UV)	UV light disrupts the DNA structure of microorganisms	Effective against many types of microorganisms	More effective in clear water environments
	b) Deoxygenation	Reduces oxygen in the space above water, thereby suffocating microorganisms	Reduces corrosion as oxygen decreases	Takes 1-4 hours to suffocate microorganisms
	c) Heat	Achieved by heating ballast water	Ballast water is disinfected as it heats during its use as cooling water.	It requires a long time for effective heating
	d) Cavitation	Breaks the cell walls of microorganisms using gas or ultrasound	Effective as a pretreatment system	Not sufficient alone to kill all microorganisms
Chemical Treatment	a) Chlorination	Breaks down microorganism cell walls	Water disinfection systems for industrial and urban applications	Ineffective against cysts if used at concentrations lower than 2 mg/l
	b) Electro-Chlorination	Creates an electrolytic environment that oxidizes, breaking down microorganism walls and	Water disinfection systems for industrial and urban applications	Ineffective against cysts if used at concentrations lower than 2 mg/l

Table 1: *Treatment methods and comparisons (continue)*

Chemical Treatment	c) Peracetic Acid and Hydrogen Peroxide	Addition to water to break down microorganism cell walls	Can result in harmful byproducts	Requires a separate storage area for high doses
	d) Ozone	Ozone gas is introduced into water, reacting with other substances, and killing organisms	Effective against microorganisms	Not effective on large organisms
	e) Menadione and vitamin K levels	Invertebrates are toxic	It can be obtained through both natural and artificial methods. No harmful effects	The treated water must be neutralized before discharge.

4 Methodology

This study employs a mixed-methods approach, integrating qualitative and quantitative research methods to evaluate ballast water treatment systems comprehensively. The research design consists of two primary stages: systematic literature review and semi-structured expert interviews. The study starts with a systematic literature review to identify important factors in choosing ballast water treatment systems, like installation and operating costs. These parameters were then refined and expanded through semi-structured interviews with seven industry experts, including three authorized representatives from installation companies and four system users. 15 thorough selection criteria were developed by combining knowledge from the two sources to direct the treatment systems' comparative analysis. Firstly, the factors considered to be important in the selection of ballast water treatment systems were identified through a comprehensive review of the relevant literature. In this review, basic parameters such as installation and operating costs were particularly emphasised; however, it was understood that these parameters alone were not sufficient for selection. In order to overcome the deficiencies of the parameters obtained as a result of the literature review, 7 industry experts with experience in the field of application were interviewed. Out of the 7 industry experts consulted, 3 are authorized in the companies that installed ballast water treatment systems and 4 are ballast water treatment system users. Information about these people is presented in Table 2.

Table 2: *Information about industry representatives*

Expert	Industry	Role
Person 1	Representative of a treatment company	Purchasing department manager
Person 2	Representative of a treatment company	Purchasing department manager
Person 3	Representative of a treatment company	Treatment system installation manager
Person 4	Ship personnel (treatment system user)	Captain
Person 5	Ship personnel (treatment system user)	Captain
Person 6	Ship personnel (treatment system user)	First Officer
Person 7	Ship personnel (treatment system user)	Chief Engineer

4.1 Parameters to Consider When Choosing a Ballast Water Treatment System

Type Approval: Ballast water treatment systems must be of the IMO type approved to comply with the BWMC. This approval is given by the flag state or organizations authorized by the flag state (Kukner

& Yasa, 2018; Wang & Corbett, 2021). Ships operating in the United States of America (USA) waters must comply with the United States BWM regime. The US administration's testing and protocol requirements are more comprehensive and more stringent than IMO's type approval requirements. The ballast water treatment system of ships conducting ballast operations in US waters must have US Coast Guard (USCG) type approval. The US authorities have paid attention to this situation (Čampara et al., 2019).

- Installation and purchase costs: These include those of ballast water systems (Wang & Corbett, 2021).
- Operating costs: This is the cost that covers expenses such as spare parts, repair, maintenance, and consumed energy by the system (Tokus, 2019).
- Damage to the environment: There is a risk that the chemicals used, especially in chemical treatment methods, may harm the environment by creating harmful by-products with other chemicals in seawater (Güney, 2017).
- Usability in fresh and salt water: Some organisms can live in fresh water, whereas others can live in salt water. This problem can be solved by installing a desalination device on board (Vural & Yonsel, 2015).
- System footprint: While the planning of the area covered by the treatment system is done in advance for ships under construction, adding a ballast water treatment system to existing ships may pose a problem for the treatment system (Tokus, 2019). In systems using chemical treatments, the storage of chemicals occupies extra space on the ship (Bilgin Güney, 2018).
- Spare parts and service: The supply and installation of manufactured parts on the ships is performed by service providers. Companies producing ballast water treatment systems focus primarily on their production processes. Installation, maintenance, and repair require an international network. These services are mostly provided by providers. Ship owners use service providers to install and maintain the treatment system (Rivas-Hermann et al., 2015).
- Personnel safety and training: If a chemical treatment method is used, necessary training should be given on the use of chemical substances for personnel safety (Tokus, 2019).
- External disruptions: In the filtration method used in ballast water treatment, disk and membrane filters are generally used. One of the important problems encountered in filter systems is clogging by large organisms found in seawater. Cleaning of these filters is done by a backwashing system (Güney, 2017).

5 Results and Discussion

5.1 Ballast Water Treatment System Selection for Chemical Tankers

An attempt was made to select the most suitable ballast water treatment system for a chemical tanker. To identify the most appropriate system, the systems were compared based on the determined parameters. Using the selection criteria specified in the Methodology section for chemical tanker A, one of the following systems will be selected and integrated on board: a filtered electrolysis system, a filtered chemical system, a filtered UV system a UV system with hydrocyclone. The tanker details are given in Table 3. The 10 parameters to be used in the selection of 4 different types of ballast water treatment systems are listed in Table 4.

Table 3: *Chemical tanker information*

Ship Type	Chemical Tanker
Year Built	2012
Length Overall	135.6 m
Beam (Width)	20.6 m
Gross Tonnage	8,975
Maximum Summer Draft	8.51 m
Summer Deadweight (DWT)	12,933.2 tons
Ballast Water Capacity	4,857.81 m^3
Ballast Pump Capacity	2 x 500 m^3/hours

Table 4: *Ballast water treatment system selection parameters*

Parameter	Description
Parameter 1	IMO type approval
Parameter 2	USCG type approval
Parameter 3	Purchase and installation costs
Parameter 4	Operating cost
Parameter 5	Environmental impact
Parameter 6	Usability of freshwater and saltwater
Parameter 7	Space occupied by the system
Parameter 8	Spare parts and service availability
Parameter 9	Personnel safety and training
Parameter 10	External disruptions

The parameters for selecting the most suitable ballast water treatment system were identified through a systematic literature review and semi-structured interviews with industry experts. These parameters were used to compare the filtered electrolysis treatment system, filtered chemical treatment system, filtered UV treatment system, and UV treatment system with hydrocyclone, as shown in Table 5. According to the comparison. Four systems compared according to parameters 1 and 2 were approved as IMO-type or USCG-type. According to Parameter 3, the installation cost of a chemical system with a filter is more advantageous than that of other treatment systems due to the efficient combination of the filter system and chemicals. The reason other systems were excluded for this parameter was that the filtered chemical system showed a more advantageous cost-benefit ratio due to the combination of chemical treatment and filtration. According to Parameter 4, the absence of a filtering system makes hydrocyclone systems more advantageous in terms of operating costs. The use of chemicals in treatment systems is disadvantageous in terms of operating costs. According to Parameter 5, the chemicals used in the filtered chemical system pose a greater risk to the environment, thus, making the other systems more advantageous. According to Parameter 6, all systems can operate efficiently in salty and fresh water. According to Parameter 7, in filtered chemical treatment systems, both the system and storage space are required on deck or in suitable spaces for storing chemicals. Therefore, other treatment systems are more advantageous than filtered chemical treatment systems. According to Parameter 8, UV systems with filters and UV systems with hydrocyclone are more frequently produced and preferred by ship owners, which makes these systems more advantageous in terms of spare parts and service. According to Parameter 9, the chemical substances used in chemical treatment systems pose a risk to personnel safety. Personnel should be trained on the use of chemical substances. Since UV systems with filters and hydrocyclones are more widely used than other systems, ship personnel are more familiar with them. According to Parameter 10, UV systems that use hydrocyclones instead of filters are more advantageous than other systems. Marine organisms that are near the treatment system and manage to clog the filters cause operational delays. As a result of the evaluation, it was determined that the most suitable treatment system was a UV system, with hydrocyclones. UV systems with filters are an alternative to UV systems with hydrocyclones. To make a clearer choice between the two systems, the operating costs obtained from the sector will be compared, and a decision on which system to install on the chemical tanker ship will be made.

Table 5: *Comparison of ballast water treatment systems*

Parameters / Ballast Water Treatment Systems	Filtered Electrolysis System	Filtered Chemical System	Filtered UV System	Hydrocyclone UV System
Parameter 1	✓	✓	✓	✓
Parameter 2	✓	✓	✓	✓
Parameter 3		✓		
Parameter 4				✓
Parameter 5	✓		✓	✓
Parameter 6	✓	✓	✓	✓
Parameter 7	✓		✓	✓
Parameter 8			✓	✓
Parameter 9			✓	✓
Parameter 10				✓

The most widely used ballast treatment systems are those in which ballast water is treated with UV radiation after separating organisms larger than 50 µm from water via filtration, or hydrocyclone (Stehouwer, 2016). In the filtration system, backwashing is necessary to ensure filter cleanliness. Pressure drops caused by backwashing prolonged the ballast water intake time (Yonsel & Vural, 2017). The CIP module in the filtered UV systems cleans the equipment at the end of the treatment process. The CIP module contains a liquid, and its annual cost is 75 Euros (Tokus, 2019). The operating expenses of UV systems with filters and UV systems with hydrocyclones are compared in Table 6. As a result of the comparison, the decision was made to install a UV system with a hydrocyclone on the chemical tanker.

Table 6: *Operating costs of the filtered and hydrocyclone UV systems*

Equipment	Filtered UV System	Hydrocyclone UV System
Filter element	Present	Absent
Filter backwash system	Present	Absent
UV lamp cleaning	Present	Cost-free
UV lamp replacement	Present	Present
Quartz tube	Present	Present

5.2 Installation of Hydrocyclone-UV Ballast Treatment System and Costs for 10 Years

As a result of the market research, the company that installs the system has been determined. Since few companies have installed this system, it was easy to choose one. The prospective company was interviewed, and its official provided data on the hydrocyclone UV treatment system and costs for 2021. The parts of the UV treatment system to be installed with a hydrocyclone are shown in Figure 1. The treatment system includes a hydrocyclone, local control panel, UV supply panel, US module, and UV module.

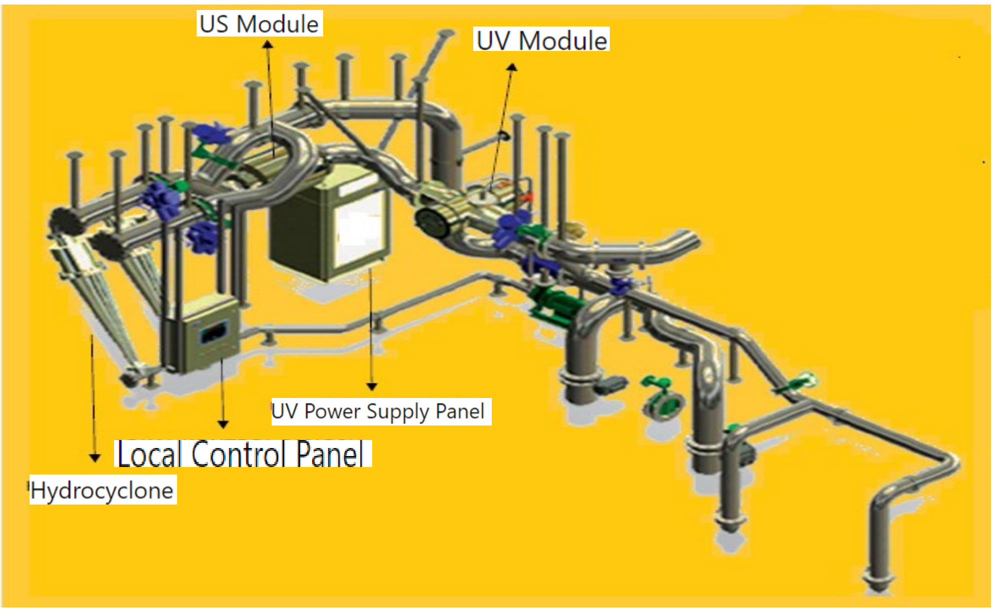

Figure 1: Isometric view of ballast water treatment system

In ships where there is not enough space, system equipment can be installed either separately, side by side, or on top of each other. There is only one rule to be followed in installation, and it is shown in Figure 2. According to this rule, the hydrocyclone unit can be placed with a maximum slope of 45° with respect to the ground. In this case, the pressure loss is only 0.6 bar or less.

Figure 2: Maximum angle of hydrocyclone system with ground

When there is not enough space for the treatment system, the installation company conducts a 3D scan and situates the system within the model drawing in the most appropriate and economical way. Sample 3D model is shown in Figure 3. The drawings will be submitted to the classification society for approval. Following class approval, the pipes and associated connection equipment to be used externally are listed together with their technical specifications. After the preparation of the pipes and connection equipment, the system installation was completed, tested under the supervision of the classification society and authorized ship personnel, and then delivered.

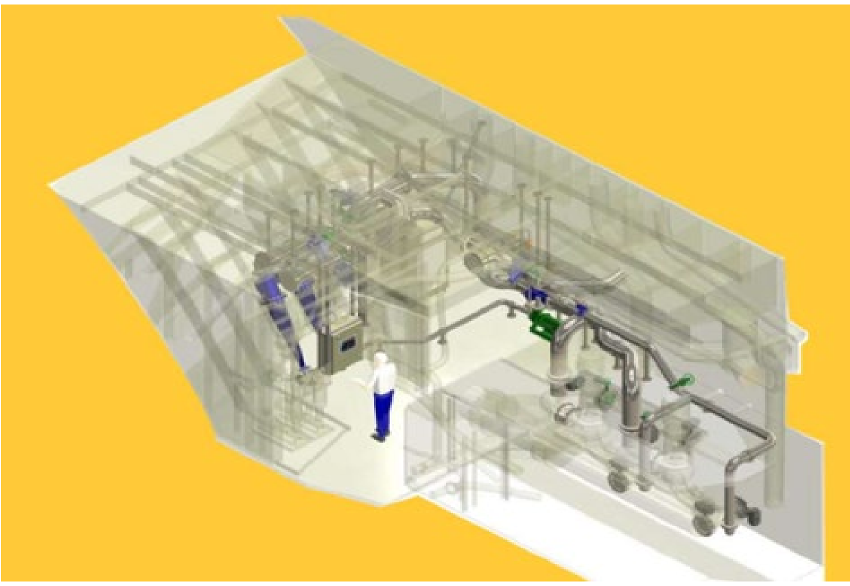

Figure 3: Demonstration of ballast water treatment system in a 3D model

The investment cost has the highest share among the costs of ballast water treatment systems (Tokus, 2019). For the investment cost, interviews were conducted with the authorized company, and the necessary information was obtained via email. The ship has two ballast pumps with a capacity of 500 m3/h. Therefore, the capacity of the treatment system to be integrated into the ship was 1,000 m^3/h. Because the ship was a chemical tanker, an explosion-proof (gas tight) system was selected. Investment costs are handled in four different groups. These are the purchase cost of the product, the installation cost of the product, the 3D modeling design cost included in the documents to be submitted to the classification societies before installation, and the extra inspection and certification cost of the flag state and classification societies after installation. These costs are listed in Table 7.

Table 7: *Cost of hydrocyclone-UV ballast treatment system*

Investment Costs	Fees (USD)
Purchase cost	175,000
Installation cost	43,750
Model design cost	15,000
Certification cost	3,000
Total	236,750

Operating costs are calculated for two different groups. These are the operational and maintenance costs. When calculating the operational cost of the ballast water treatment system, the consumed energy by the ship was also calculated. It is assumed that the ship performs 20 operations per year. Ballast intake time is calculated as 10 and 12 hours. The annual ballast operation time was calculated as 440 hours. The energy cost per kilowatt (kW) was calculated as 0,1 USD. The energy costs of the 1000-m3/h capacity system are listed in Table 8. The amount of electrical energy consumed by the system for 10 years was 234,520 kWh, and the cost of the consumed energy was USD 23,452.

Table 8: *The consumed energy by the system and its cost*

Description	Value
Minimum-Maximum Power (KW)	36-82 kW
Average Power (KW)	53,3 kW
1-Year Electrical Consumption	23,452 kW
1-Year Electricity Cost	$2,345
5-Year Electrical Consumption	117,260 kW
5-Year Electricity Cost	$11,726
10-Year Electricity Consumption	234,520 kW
10-Year Electricity Cost	$23,452

Ballast water treatment system equipment is maintained or replaced at regular intervals. The maintenance cost is required for the maintenance or replacement of the system equipment. Among the equipment that is maintained and replaced, the flow meter, UV, temperature, and pressure sensors are calibrated every year; the UV lamp is replaced every 3 years; the quartz wiper is maintained every 3 years; the quartz tube and ultrasonic boiler are replaced every 5 years; and electrical and solenoid valves are maintained every 5 years. There is also a service cost for the class. According to the data received from the manufacturer, the detailed maintenance costs are listed in Table 9 for the annual, 5-year, and 10-year periods.

Table 9: *Maintenance costs of hydro cyclone-UV ballast treatment system*

Equipment List	Maintenance or Replacement Time	Maintenance or Replacement Cost (USD)	1-Year Cost (USD)	5-Year Cost (USD)	10-Year Cost (USD)
Hydrocyclone	-	-	-	-	-
Flow Meter	Calibration / Annually	160	160	800	1600
Temperature & Pressure Sensors	Calibration / Annually	160	160	800	1600
UV Sensor	Calibration / Annually	160	160	800	1600
Drain Pump	Maintenance/ 5 Years	580	116	580	1160
UV Lamp	Replacement/ 3 Years	600 per unit	1200 (up to 250 m³)	6000 (up to 250 m³)	12,000 (up to 250 m³)
Quartz Wiper	Maintenance Seal Set / 3 Years	100 per seal set	33	166	332
Quartz Tube	Replacement/ 5 Years	200 per unit	240 (up to 250 m³)	1200 (up to 250 m³)	2400 (up to 250 m³)
Ultrasonic Boiler	Replacement/ 5 Years	8800	1760	8800	17,6
Electric Valves	Maintenance/ 5 Years	1000	200	1000	2000
Solenoid Valves	Maintenance/ 5 Years	200	40	200	400
Service for Class	Annually	300	300	1500	3000

UV lamps, ultrasonic boilers, and quartz tubes constitute a significant part of the maintenance cost. The number of these parts increases as the system capacity increases, in this case, the maintenance costs also increase. As the number of UV lamps in the system increases, the energy drawn by the system also increases. An excessive amount of energy drawn from energy systems causes increased usage, which indirectly increases the maintenance cost. The annual 5-year and 10-year total maintenance and replacement costs obtained from the data on the ballast water treatment systems built on the 450 ships are listed in Table 10.

Table 10: *Total maintenance cost of the ballast water treatment system*

Capacity (m³)	1-Year Total Cost	5-Year Total Cost	10-Year Total Cost
100-250	$4,369	$21,846	$43,692
500-700	$5,569	$27,845	$55,690
1000-1500	$6,769	$33,845	$67,690

According to the data obtained, the annual maintenance and repair cost of the ballast water treatment system with a capacity of 1000 m3 is USD 6,769, the 5-year maintenance and repair cost is USD 33,845, and the 10-year maintenance and repair cost is USD 67,690. The 10-year total cost (CTM) of the ballast water treatment system, with a capacity of 1000 m3, is equal to the sum of the investment cost (CYM), 10-year operational cost (COM), and 10-year maintenance and overhaul cost (CBTM). The 10-year total cost is shown in Equation 1.

$$C_{TM} = C_{YM} + C_{OM} + C_{BTM} \tag{1}$$

According to the created equation;

$$C_{TM} = 236750 \text{ USD} + 23452 \text{ USD} + 67690 \text{ USD} \tag{2}$$

$$C_{TM} = 327892 \text{ USD} \tag{3}$$

In the study conducted, when examining the costs of the ballast water treatment system, it was found that the investment was the highest cost, amounting to 236,750 USD, followed by maintenance costs at 67,690 USD, and operational costs were the lowest at 23,452 USD. In proportional terms, 72% was attributed to investment costs, 21% to maintenance costs, and 7% to operational costs.

The findings of this study align with existing literature on ballast water treatment systems, particularly regarding system selection criteria and cost-effectiveness. Similar to previous studies (Bashan & Kaya, 2022; Vorkapić et al., 2018), UV-based treatment systems are favored for their low maintenance, high energy efficiency, and minimal environmental impact. While filtered chemical treatment systems may have lower installation costs, their higher operational expenses and environmental risks make them less favorable (Kato & Kansha, 2024). The literature also highlights the importance of space requirements, spare parts availability, and operational disruptions, which are consistent with this study's findings. Hydrocyclone-UV systems are advantageous due to their lack of filter backwashing, reducing operational delays. Cost evaluations show that while UV-based systems may have a higher initial investment, their long-term operational and maintenance costs are more manageable. Energy consumption and maintenance align with industry expectations, further supporting the practicality of hydrocyclone-UV systems for chemical tankers. Overall, the study emphasizes that the selection of a treatment system should consider the type of ship, operational needs, and compliance requirements, rather than focusing solely on cost.

6 Conclusions

Important parameters for the selection of ballast water treatment systems were determined, and information on the costs of such systems was obtained. This study aims to contribute to the sector by providing information to companies that will install this system on their ships. Within the scope of the study, a ballast water treatment system suitable for tanker A, with 12933 DWT, was selected, and the total cost of this system over 10 years was calculated. First, the treatment method must be selected. For this purpose, 10 selection parameters were created by reviewing the literature and interviewing experts. With the help of these parameters and expert opinions, the hydrocyclone / UV system was selected for ship A. The companies that are installing this system were identified. The number of companies installing hydrocyclone/UV treatment systems in our country is not very high. For the cost calculation, a company official was contacted to obtain the necessary information. The company and ship names were not disclosed due to commercial confidentiality. According to the received information, the total cost of the installation and 10-year operation of the hydrocyclone/UV system was USD 327,892. Of this cost, 72% is investment cost, 21% is maintenance cost, and 7% is operational cost. Although investment cost is primarily important for ship owners in ballast water treatment systems, maintenance and upkeep costs should be taken into consideration as well.

In this study, a chemical tanker ship was examined. The ballast intake and discharge capacity of oil tankers is higher than those of chemical tankers. In future studies, research can focus on issues related to crude oil tankers and similar vessels. In this way, it will be beneficial for the maritime sector if the owners of large-tonnage ships have an idea about this issue. Additionally, future research could explore advancements in treatment technologies, optimization strategies to reduce energy consumption, and regulatory changes affecting system selection.

7 Declarations

7.1 Study Limitations

There is no limitation.

7.2 Acknowledgements

There is no person or institution contributing to this research other than the authors.

7.3 Funding source

No financial support was received for this research.

7.4 Competing Interests

There is no conflict of interest in this study.

7.5 Authors' Contributions

Serkan BARIS: Developing ideas or hypotheses for the research and/or article, planning the materials and methods to reach the results, taking responsibility for the experiments, organizing and reporting the data, taking responsibility for the explanation and presentation of the results, taking responsibility for the literature review during the research, taking responsibility for the creation of the entire manuscript or the main part.

Sayit OZBEY: Organizing and reporting the data, taking responsibility for the explanation and presentation of the results, taking responsibility for the literature review during the research, taking responsibility for the creation of the entire manuscript or the main part, reworking not only in terms of spelling and grammar but also intellectual content or other contributions.

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