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DEVELOPMENT DYNAMIC COMPLIANCE COST MODEL FOR IMPLEMENTATION OF BALLAST WATER MANAGEMENT CONVENTION: SHIPOWNER PERSPECTIVE

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The Ballast Water Management Convention (BWMC) regulates ship ballast water management to avoid the spread of aquatic invasive species. The convention requires all ships, including existing ones, to have a Ballast Water Treatment System (BWTS) onboard before September 8, 2024. There are some concerns about the compliance costs of BWMC, especially the additional cost of retrofitting cases. The ship retrofitting cost will depend on various factors, and it can be difficult for a shipowner to determine accurately. The procedure is intricate, and there are many factors to consider, such as the ship's size, BWTS system complexity, and the price of materials and modification level. In this paper, A proposed approach involves expert judgment to capture the effect of multi-stakeholder and estimate the compliance cost. As an essential part of the research methodology, the system dynamics method and life cycle cost are combined to develop a compliance cost model during the ship's lifetime. The simulation model shows that the confidence level of retrofitting costs for each BWTS is more than 94%. Therefore, the model can be used to estimate additional costs. As a result, BWTS type A is the most economical system for small tankers, with an estimated cost of USD 802,860 for the remaining 12 years of the ship's lifetime. Shipowners can use this model as a supporting decision tool to determine which BWTS would be suitable and assist in determining the budget necessary to comply with the BWMC.

Keywords: ballast water treatment, retrofitting, compliance cost, system dynamics, life-cycle cost

1 INTRODUCTION

The International Maritime Organization (IMO) adopted the International Convention for the Control and Management of Ships' Ballast Water and Sediments. The Ballast Water Management Convention (BWMC) establishes the standard for managing and controlling water and vessel sediments to prevent the spread of dangerous invasive species from some area to another. The BWMC requires ships to manage their ballast water and sediments to a certain standard, depending on the volume of water they carry and the date of their construction [1]. BWMC has Ballast Water Exchange (D-l Standard) and Ballast Water Treatment (D-2 Standard).

Ballast water exchange (BWE) may not always be the best option for managing ballast water due to weather-related challenges. The BWE method is not feasible in some conditions because it requires stable sea conditions, limiting the areas available for exchange, causing delays, and lowering effectiveness. These difficulties make the BWE method considered a secondary method before resorting to Ballast Water Treatment System (BWTS). According to the established schedule, the ship must be installed BWTS before September 8, 2024 [2]. The specific timeline for installation is contingent upon the ship's construction. The requirement is directly associated with renewing the International Oil Pollution Prevention (IOPP) certificate [3]. Shipowners need to plan and budget accordingly to ensure that their ships comply when the time comes for the renewal of their IOPP certificate. It involved marine engineers, classification societies, and industry experts in determining the best course of action and ensuring that the installation process was completed promptly and efficiently [4].

Installing BWTS on board is the shipowner's responsibility. Installing on existing ships is more complex than on new construction ships. It is caused by the ship design does not consider adding a new system. The installation of BWTS on existing ships will affect the construction, ship components, power requirement, pump rate, available area (footprint), and payload. The estimated initial purchase and installation cost can spend 0.2 to 1 million USD per vessel, depending on its capacity and treatment method [5]. Even though using the same BWTS, the compliance cost of each ship will be different due to varying difficulty and challenge levels [6].

Available guidelines merely describe the compliance process but are missing to describe how to calculate the cost incurred [7]. The additional cost is crucial for shipowners in considering strategies to comply with the convention. Thus, shipowners require a comprehensive study to consider pressing factors such as multiple stakeholder interactions and dynamic parameters impacting compliance costs. Implementing ballast water management requires initial capital expenditures for purchasing the necessary equipment and ongoing costs for operation and maintenance. The operation and maintenance costs of BWTS can significantly impact its reliability throughout its lifetime. Therefore, these are vital factors to consider when evaluating the overall reliability of a BWTS through a life cycle cost analysis [8].

Life cycle costs comprise construction, operation, and maintenance costs during the lifetime of a ship. Shipowners can select the most cost-effective and efficient BWTS system that meets all the requirements by conducting a comparative analysis of various BWTS methods and considering the initial and operational costs. Some studies have slighted the operation cost variable because it is small compared to the retrofitting cost. However, this must be taken into account when calculating compliance costs. This research aims to develop a model with an integration life-cycle cost component to identify factors that may increase compliance costs.

This paper consists of four main sections. The first section determines the originality, methods' significance, and applicability. This section also explains why shipowners need a model to predict compliance costs. The second section is the literature review, which describes how to estimate and evaluate compliance costs. The third section identifies each stage of system dynamics and life-cycle approach integration for developing models. The last section observes and analyses the system response to select suitable BWTS based on compliance cost. A compliance cost model using system dynamics is proposed for to cost estimate of BWMC implementation.

2 LITERATUR REVIEW

Ballasting and de-ballasting are crucial aspects of shipping, especially for stability and safe navigation. It is achieved by transferring water from one port to another during cargo operations. The practice helps to reduce hull stress caused by unfavorable sea conditions, changes in cargo weight, fuel consumption, and water consumption. However, the discharge of ballast water has posed significant environmental, economic, and public health concerns. IMO enacted the International Convention for the Control and Management of Ships' Ballast Water and Sediments in 2004 to reduce the transfer of dangerous aquatic organisms and pathogens in ships' ballast water [1].

The BWMC was already ratified by 35% of the world's marine tonnage and entered into force on September 8, 2017. It mandates that all ships, especially those operating on international routes, must be installed with a BWTS. The installation of the BWTS must conform to the D-2 requirements [9]. The BWTS technology installation schedule is determined based on the ship's construction. The vessels built after September 8, 2017, should comply with D-2 standards from delivery time, while existing ships built between September 8, 2014 to September 8, 2017 should comply with the requirement on the first IOPP Certificate renewal. The vessels constructed before September 8, 2014 should comply with the requirement on the second IOPP renewal survey.

Shipowners must invest in a BWTS that meets the D-2 standard. The investment amount depends on the compatibility of the chosen BWTS with the ship's resources. Each ship has different characteristics, such as tank capacity, pipeline system, pump flow rate, and power availability. Several analysis methods for selecting BWTS use the analytic hierarchy process (AHP) approach. The goal is to optimize the results involving various criteria and consider the vessel's specifications. Water characteristics such as salinity, temperature, PH, and turbidity based on shipping routes are also factors that influence BWTS technology selection [10]. Several researchers have proposed a mobile port-based BWTS alternative that would allow vessels to comply without carrying BWTS on board [11].

Ships also can discharge ballast water at the port, where it is treated before being released into the environment. This alternative can benefit shipowners with insufficient space or resources to install a BWTS onboard. It also allows for more centralized and efficient management of ballast water treatment. However, it requires cooperation between ports and shipowners and may entail additional costs and logistic challenges. The alternative on land shore is treating on land rather than on the ship. This alternative can be more efficient and cost-effective for shipowners because it eliminates the cost of onboard installation and maintenance [12]. Some research has analyzed potential opportunities from this alternative as port service products [13]. Studies about reception facilities are expanding because it is low cost and considered easy to oversee implementing this convention [14]. Currently, most ports lack reception facilities, which requires shipowners to install BWTS on their vessels. Some shipowners are unsure about the extra cost and need a preliminary study before deciding to retrofit their ships.

IMO suggests the Formal Safety Assessment (FSA) approach, which can assess the implementation of new regulations [15]. However, this approach is limited in estimating financial impact, such as compliance costs perspective from the shipowner. Alternatively, the American Bureau of Shipping (ABS) recommended the Life-cycle cost (LCC) approach to calculate total shipowner cost as the financial impact of retrofitting, especially the installation of ballast water treatment [8]. Some researchers use the LCC to analyze cases of ship retrofitting, such as using it as a framework for retrofitting marine engines to reduce emissions[16] and a selection tool for retrofitting alternatives [17]. These studies' results indicate the LCC's ability to calculate all retrofit cost elements. However, these studies still skip essential factors about the implementation schedule and duration.

The weakness of the LCC approach is its limitations in integrating uncertainty problems from the retrofitting process. LCC has typically been used in conjunction with the Life Cycle Assessment (LCA) method rather than as a standalone approach [16]. LCC has difficulties predicting future costs and benefits, accounting for all relevant factors, addressing uncertainties and risks, and incorporating changes over time. These difficulties highlight the need for caution when using LCC for complex systems. Many researchers have combined the methods of LCC and System Dynamics to address complex problems. System dynamics is an approach to understanding the behaviour of complex systems over time, particularly how they change and develop through the interaction of their parts [18]. When combined with LCC, which focuses on analyzing the costs and benefits of a system throughout its entire lifetime, these methods provide a comprehensive approach to solving complex problems. This combination can estimate the impact of the observed system change over time while calculating each subsystem's correlation [19]. The systems dynamics method can enhance the limitations of the LCC method. The principle of system dynamics is to analyze all elements of complex dynamic feedback systems and observe the system's performance over time to predict the behavior of complex systems [20,21].

Even though system dynamics has never been used to estimate compliance costs, some reviews show that its approach successfully observes the regulation's effects, especially in dynamic economic impact [22]. The system dynamics are applied to resolve operational problems in the maritime sector. It is beneficial to analyze the design of a port-economy system and describe the interaction of critical components between the port and the economy. The analysis focuses on the inflow and outflow of elements and their impact on the system's performance over time. Some literature research has confirmed that system dynamics methods help address complex and dynamic problems [23]. It is also beneficial in determining the strategy for implementing new regulations compared to other methods. According to the review, combining LCC and system dynamics is a powerful approach that can estimate the cost of implementing new regulations and allows for dynamic monitoring of variables and systems.

3 METHODOLOGY

This research presents a model that integrates the LCC approach with the system dynamics simulation. The integration of these two approaches provides a comprehensive framework for ship retrofitting cases in the marine industry. The combination can be seen in Fig. 1, which describes the relationship between each step. Integrating the Life Cycle Cost (LCC) approach and system dynamics model aims to identify all cost elements from the LCC approach and incorporate them into developing a system dynamics simulation model. The LCC approach considers all costs over the lifetime. The element cost is acquisition, operation, and maintenance costs. Especially for retrofitting the ballast water system, LCC involves evaluating the costs associated with cost elements that consist of Design and planning costs, procurement, installation, operating and maintenance costs, and financing costs. These cost elements should be considered when conducting an LCC analysis for a retrofitting project to determine the total cost of a shipowner. Retrofitting cost can be determined through the following equations.

$$C_R = C_D + C_P + C_I + C_{Ad} = \sum_{1}^{n} C_n \tag{1}$$

Where; C_R is Retrofitting cost (USD), C_D ; Drawing Design Cost (USD), C_P ; Procurement Cost (USD), C_I ; Installation Cost (USD), and C_{Ad} ; Additional Cost (USD). LCC can determine through the following equations.

$$LCC = C_R + C_O + C_M \tag{2}$$

Where; LCC is Life-cycle cost (USD), C_M ; Maintenance Cost (USD) and C_O is Operation Cost calculated following equation 3 and multiplied by the oil price per barrel.

$$FOC = \sum_{i=1}^{n} P_i \; . \; SFOC_i \; . \; H_i \tag{3}$$

Where; FOC is fuel oil consumption (barrel), P ; power required for each operation (kW), $SFOC_i$; specific fuel oil consumption under specific engine output (g/kWh), H_i is yearly operating hours for each operation mode (hour/year) and i refers to different type BWTS.

The problem is identified through literature reviews, expert judgment, and interviews, and then the information is used to build a mathematical model. The LCC approach follows the guidelines in ISO15686-5 and includes several steps, such as defining the research aim, breaking down the system into components, creating a conceptual model, formulating the system model, running simulations and analysis, and evaluating the results [24]. The LCC approach helps make informed decisions about investments by evaluating the long-term costs of a system. In this case, the stage of the LCC approach is adopted from the LCC framework to analyze retrofitting engine systems as an additional reference [25]. The LCC and system dynamics stages are similar. It involves defining the problem, creating a conceptual model, and evaluating the results through simulation and analysis. Exactly, LCC focuses on the total cost of a system over its life cycle, while system dynamics focuses on modeling the behavior of a complex system over time. The model of system dynamics uses stocks and flows as diagrammatic notation. The stock serves to accumulate all elements connected with the flow every time. The mathematical equation that represents this stock follows the following equation

$$Stock(t) = \int_{t_0}^{t} [Inflow(s) - Outflow(s)] ds + Stock(t_0) \tag{4}$$

The *stock* is a variable that changes over time, impacted by initial conditions, *inflow*, and *outflow* within a specified time interval.

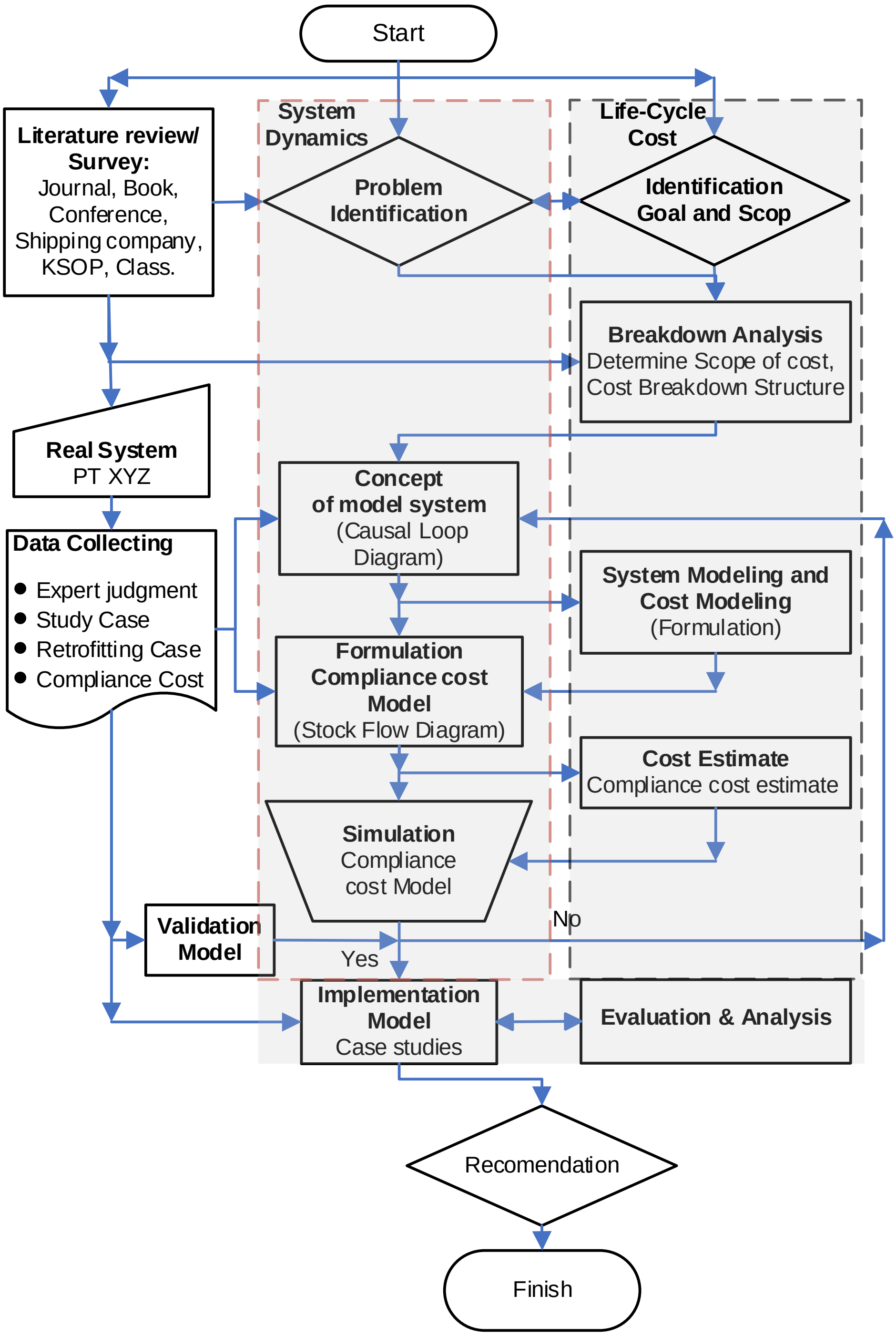

Fig. 1 Flowchart of research

3.1 Problem Articulation

The LCC refers to the total cost of the ship's design, construction, operation, and maintenance. The total cost would need to consider all relevant factors, such as the design cost, procurement, cost of materials and labor, cost of energy and fuel, cost of repairs and maintenance, and expected lifetime of the ship. The fundamental problem is that the estimation of compliance costs is not appropriate because it ignores the elements of time and duration of the system. It can be significant discrepancies between the compliance cost estimate and the actual cost. Inaccurate cost estimates can impact the project's financial viability and mistake in decision-making.

3.2 Formulation of Dynamic Hypothesis

The Dynamics Hypothesis seeks to determine the correlation between elements within a complex system. In order to achieve this objective, a qualitative approach based on hypothesis formulation is used to develop a Causal Loop Diagram (CLD). The CLD serves several essential functions, including defining system boundaries, creating subsystem diagrams, and establishing a basis for policy development. Additionally, the CLD visually represents the causal relationships, feedback loops, and interconnections between variables within the system. The life cycle of a system encompasses multiple cost components, such as retrofitting, operation, and maintenance costs over its lifetime. External costs, such as losses from downtime, are also considered during the operation phase. The Cost

Breakdown Structure (CBS) is a tool utilized to categorize costs into various levels of detail in order to account for expenses in the present study. As depicted in Fig. 2., the first level of the CBS consists of three main cost categories: Retrofitting cost, Operation cost, and Maintenance cost. The second and third levels delve further into the specific cost components per task for each party involved.

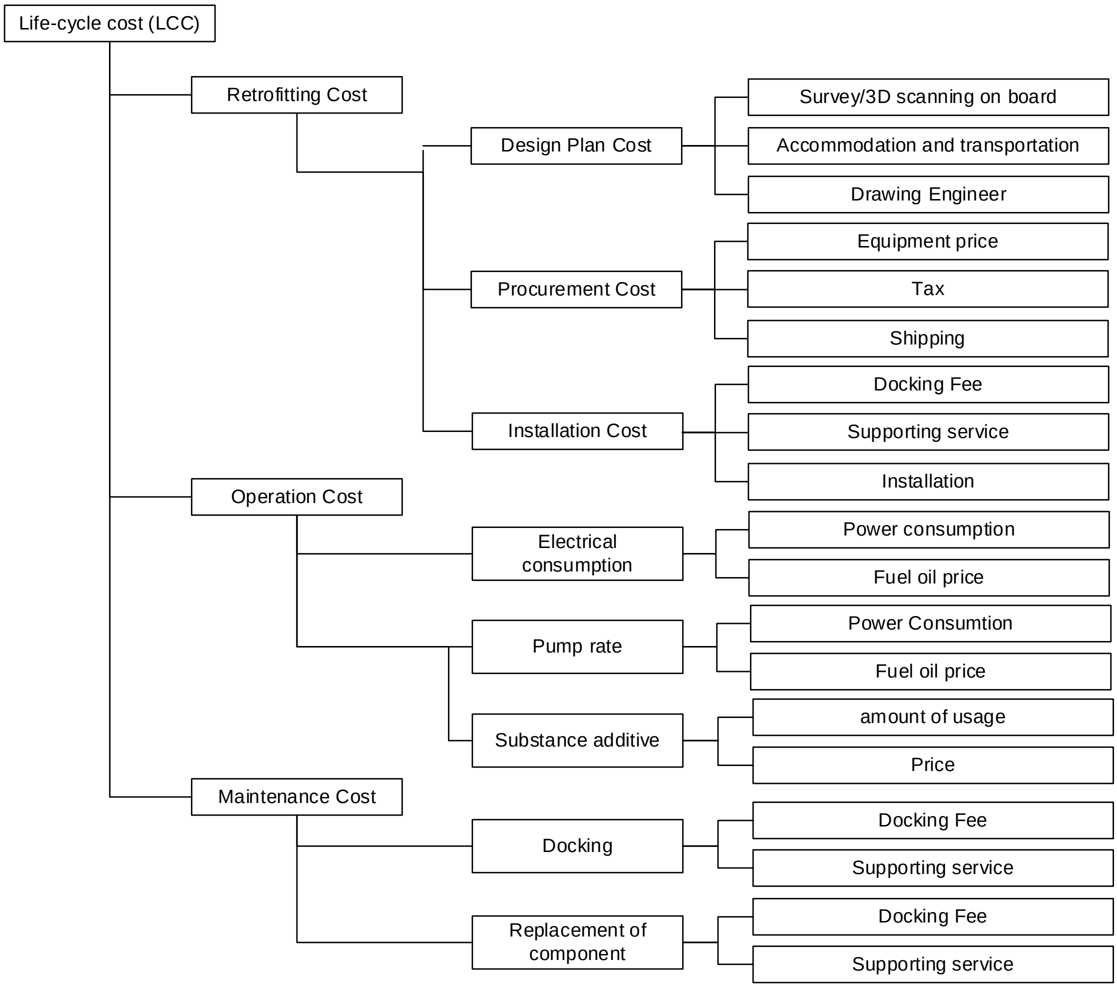

Fig. 2 Cost breakdown structure of implementation BWM convention

The elements of Retrofitting costs include Design, Procurement, and Installation costs. Operation and Maintenance costs include operating costs associated with the installed BWTS, such as electricity consumption, substance additives, replacements, and spare parts. These elements are analyzed to understand their impact on the main cost elements by breakdown into sub-elements at the detail level. Comparing CBS and expert judgment results help understand the interactions and responsibilities among the parties involved in the CLD of the compliance process.

3.3 Formulation of a Simulation Model

The compliance cost associated with retrofitting a ship with a BWTS must have been estimated using the concepts of system dynamics, which entailed simulating the interactions of many components. The components and cost elements used to make hypotheses based on the study cases. The dynamics hypotheses are generated in the formulation phase to serve the stock-flow diagrams. The causal loop diagram in Fig. 3 describes the causal relationships between variables as the base system for building a Stock-Flow Diagram (SFD). Relationships between variables in causal loop diagrams have a formulation based on the SFD.

The purpose of the SFD diagram is to detail the relationship between variables and determine the influence of time and the implementation convention. The constituent components of each sub-model interact with each other and are related and marked with arrows. The formulation of compliance cost consists of six sub-models representing elements affecting compliance costs. The six sub-elements are:

- The Design engineer sub-model.

  The design engineer model consists of design costs, including expenses incurred during the development of the retrofitting plan, such as survey or 3D scanning, consultancy, and engineering services. The cost spent to create detailed design drawings and specifications for the retrofitting project. These include fees for professional services such as design, engineering, and project management.

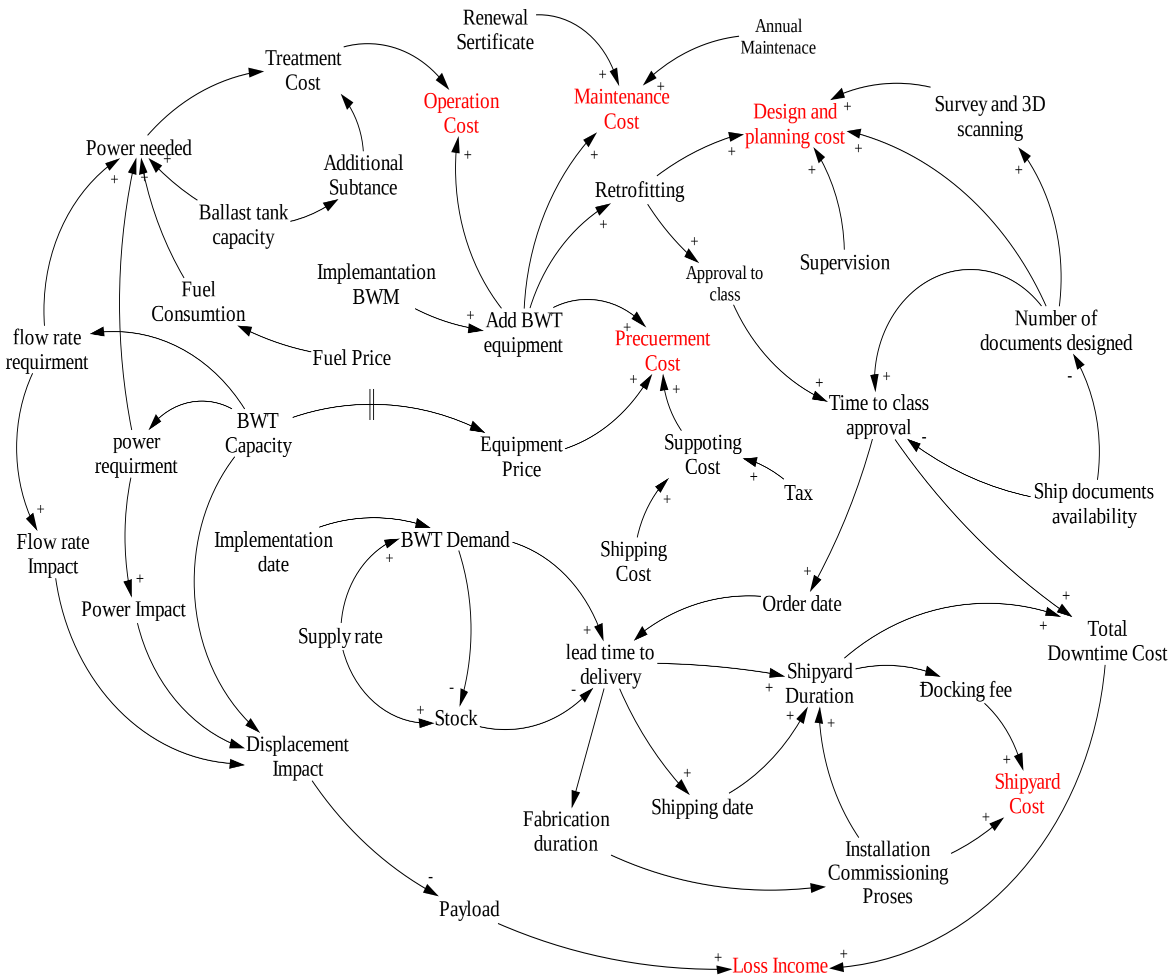

Fig. 3 Causal Loop Diagram (CLD) of Compliance cost

– Procurement sub-model.

The procurement model includes costs for acquiring materials, equipment, and services for the retrofitting project, such as equipment and materials price, shipping cost and handling, Insurance, taxes, and duties.

– Shipyard sub-model.

The shipyard model describes incurring of BWTS installation, such as the docking fee, installation, labor costs, inspections, testing, and commissioning. Another cost calculates from the vessel's downtime duration and cost of downtime during the installation process, such as fabrication duration, lead time, and delivery duration. There is a potential impact on the ship's operations and schedule.

– Operation cost sub-model.

The operational cost includes expenses incurred during the regular operation of the BWTS system, such as crew and training costs and energy consumption. Energy consumption required to run the BWTS system consists of electricity, fuel, and substances.

– Maintenance cost sub-model.

The maintenance cost consists of regular maintenance and repair of the BWTS system. The additional cost calculates from purchasing and replacing parts damaged over time.

– Loss income sub-model

A factor impacting the loss of income is downtime. Downtime can cause a ship to lose income while it runs on a tight schedule and has high daily costs. It represents the financial impact of any interruption to the ship's operations during the retrofitting process, such as during the installation or maintenance of the BWTS system.

All cost elements are essential components of compliance cost and must be accurately estimated to ensure that the retrofitting project is financially viable. A comprehensive strategy considering cost and duration is essential for successful project management and minimizing procurement costs. The model can help decision-makers to understand the costs involved, make informed choices, and plan for a successful retrofitting project.

3.4 Testing

Testing a simulation model entails comparing the model's outputs and actual observations of the real-world system. It can be performed using various techniques, including sensitivity analysis, scenario analysis, and validation against historical data. The testing aims to assess the model's correctness, dependability, and validity in simulating the system. The results use to modify and improve the model, assuring its consistency and applicability to the investigated real-world system.

The testing stage consists of three steps: running, verification, and validation. Model verification aims to test model units and variables by the consistency of each variable and unit. The validation model employs structure and parameter tests. In addition, the parameter test assesses the suitability of the simulation submodel connection. Verification of structure and parameters use expert judgment and literature studies. The result obtained the relationship of the interrelationships of variables depicted in the causal loop diagram, such as retrofitting costs, processing duration, and operational and maintenance costs.

External factors such as ship documents' availability, shipyards' selection, and suppliers' selection can also contribute to increased costs. It also potentially increases the retrofitting implementation duration and affects ship downtime. The model structure is considered valid if the relationships between the variables in the model accurately reflect the relationships in the real-world system. It includes the interaction of each variable and its impact on the observed system destination. Validation of the model through consistency testing and comparison with actual data is essential to ensure its accuracy and relevance. An Average Variance Error (AVE) is used to evaluate the accuracy of a model's predictions. It measures the deviation between actual values and predicted values, expressed as the ratio of the variance of the differences between the actual and predicted values to the variance of the actual values. The acceptable value of the AVE depends on the specific requirements of the system and the application.

3.5 Policy Design and Evaluation

Policy design and evaluation are used to analyze the compliance cost model. The model can help understand the system's dynamics, including the impact of various factors on the cost of retrofitting. In policy design, the model is used to evaluate scenario options and their potential impacts, such as improving the availability of ship documents or streamlining the selection process for shipyards and suppliers and reducing compliance costs. In policy evaluation, the model can be used to assess the impact of implemented policies and compare the outputs with actual data and observations to determine the effectiveness of the policies in reducing costs. The policy evaluation results can be used to refine and improve the policies, ensuring efficiency and effectiveness.

4 ANALYSIS AND RESULTS

4.1 Analysis Data and Simulation Model

The Compliance Cost Model estimates the costs associated with retrofitting ships to comply with requirements and standards. The model is developed using historical data, expert interviews, technical reports, market quotes, and journal articles [26]. Several existing tankers from oil shipping companies have installed BWTS, shown in Table 1 . Vessels with Small Tanker type, General Purpose (GP), Handysize, and Aframax are used as samples from historical data, and it will be a boundary of this model.

Table 1. Historical data of retrofitted tankers installed with BWT system

Ship Category	DWT (ton)	Flow rate (m3/hr)	Ballast tank capacity
Small Tanker (ST)	6.500	150	3.485
General Purpose (GP)	17.766	500	10.636
Handysize	29.760	650	18.220
Aframax	88.312	1500	43.363
Aframax	110.362	1800	42.017

Tankers can be categorized based on size (Dead Weight Tonnage). There are several types, including Small Tankers (less than 10,000 DWT), General Purpose (10,000 to 25,000 DWT), Handysize (25,000 to 40,000 DWT), Medium (40,000 to 55,000 DWT), Panamax (55,000 to 80,000 DWT), Aframax (80,000 to 120,000 DWT), Suezmax (120,000 to 160,000 DWT), and Very Large Crude Carriers (VLCC) and Ultra Large (more than 160,000 DWT).

The American Bureau of Shipping (ABS) has reported the most common Ballast Water Treatment Systems (BWTS) used in ships. These systems use various methods to treat the water in ballast tanks to prevent the spread of invasive aquatic species. The most common BWTS include filtration+chlorination (5.0%), filtration+deoxygenation (0.2%), filtration+direct-flow electrolysis with neutralization (17.8%), filtration+side-stream electrolysis with neutralization (29.0%), filtration+UV treatment (20.7%), full flow (in-line) electro chlorination (7.5%), and ozone treatment with neutralization (19.9%) [27]. The popular BWTS technology is filtration+UV treatment (Technology A), filtration+direct flow electrolysis (Technology B), and filtration+side-stream electrolysis (Technology C) [28]. There are many BWTS technology available in the marketplace, but in this study, the popular BWTS technology uses as a sample for the data input model.

The cost components of the BWTS are the equipment price, energy consumption, maintenance costs, and operational costs. These costs depend on the flow rate capacity of the BWTS technology. The available data on BWTS is limited, so a regression model is used to fill in the missing data. The regression approach uses a mathematical equation to describe the relationship between the flow rate capacity and BWTS cost. This equation can also predict other BWTS parameters based on the flow rate capacity.

The regression method demonstrates the relationship between the flow rate capacity of the BWTS technology and several parameters, such as price, power requirements, and operational and maintenance costs. The most suitable type of regression is selected by comparing the error value and R^2. This information is used to update the database for the price compliance cost model.

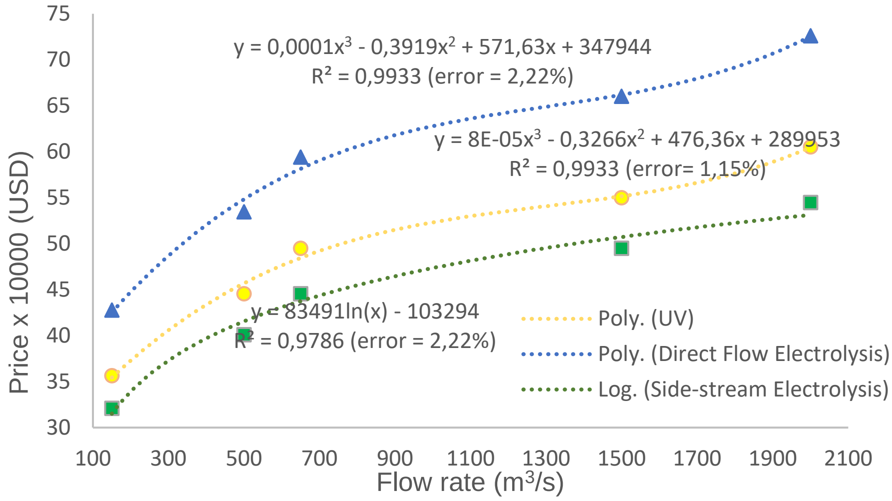

Fig. 4 Correlation of BWTS capacity and price

The BWTS price regression analysis indicates that type C technology is the most cost-effective, while type B is the most expensive. The regression models for equipment price are reliable, with an error value of less than 5% and an R^2 value greater than 90%. It indicates a strong correlation between the observed data history and the models, making the price regression model in Fig. 4 a helpful database for model reference. The power requirement and weight of the BWTS are also found to increase proportionally with the treatment rate, as shown in Fig. 5. The power is determined using a polynomial regression model with an error value of less than 7% and an R^2 value greater than 90%. The weight is determined using a polynomial regression model with an error value of less than 1% and an R^2 value greater than 90%. These results demonstrate the reliability and accuracy of the models used in the analysis. Overall, the regression analysis model evaluates the relationship between the treatment rate, price, power, and weight of BWTS. The models' low error and high R^2 values indicate high confidence in the results, making them valuable for decision-making. These results can estimate the cost, power, and weight of each type of BWTS technology, allowing for more informed decisions maker.

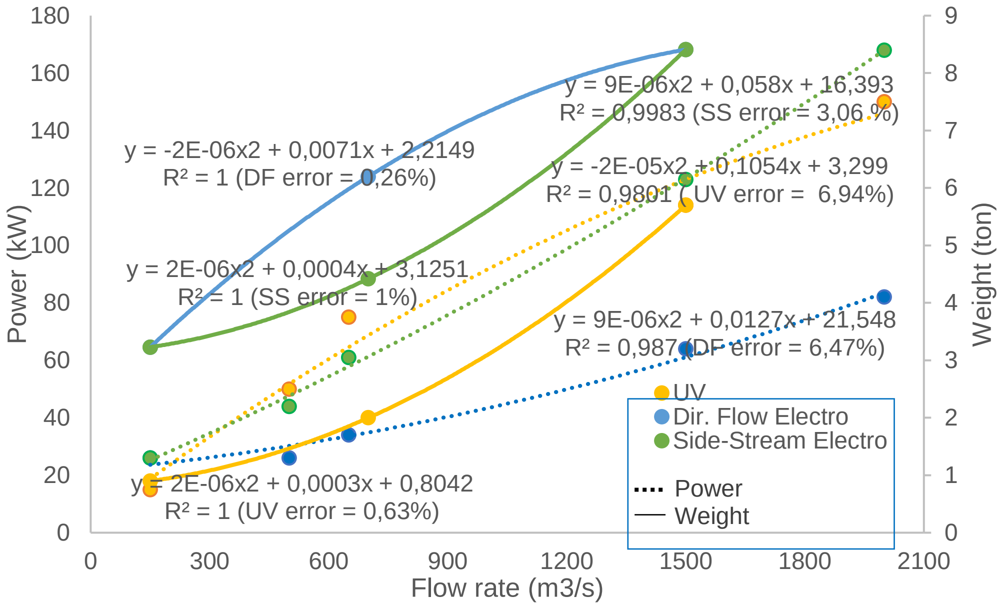

Fig. 5 Correlation of BWTS capacity, power requirement, and weight

The selection of the BWTS type requires consideration of the power parameters to ensure a match between the power requirements and the power available on the ship. The installation of the BWTS will affect the ship's electricity and have a subsequent impact on the load. The consequences of a power mismatch between BWTS requirements and available power on a ship can lead to increased costs and weight. In another part, the weight of the BWTS is also an essential parameter to consider because it will affect the ship's displacement. Modifying the pump rate or upgrading it may be necessary to address the mismatch, leading to further expenses. The maximum tolerance of the ship's weight increase should be less than 2% of Light Weight Tonnage (LWT). The power and weight should be considered when installing the BWTS technology because it is a crucial aspect of impact. The water characteristics, such as salinity, turbidity levels, and power consumption as influence parameters, should be considered. However, in this study, they are negligible because of limited data.

The cost element of installing, fabricating, and supervising BWTS technology is shown in Fig. 6 and Fig. 7. The installation and fabrication cost depends on the size of the ship, defined using correlation with Dead Weight Tonnage (DWT). The cost of installing BWTS technology on a ship increases with the size of the ship. Larger ships require more work and materials volume, like pipes and valves. The cost of supervision is based on the amount of work. The models used to calculate these costs for each type of BWTS technology have an accuracy of less than 3% and a strong correlation (R^2 more significant than 90%), which means they can be relied upon for cost estimations. Type B and C of the technology have similar fabrication and supervision costs because they use chemical methods.

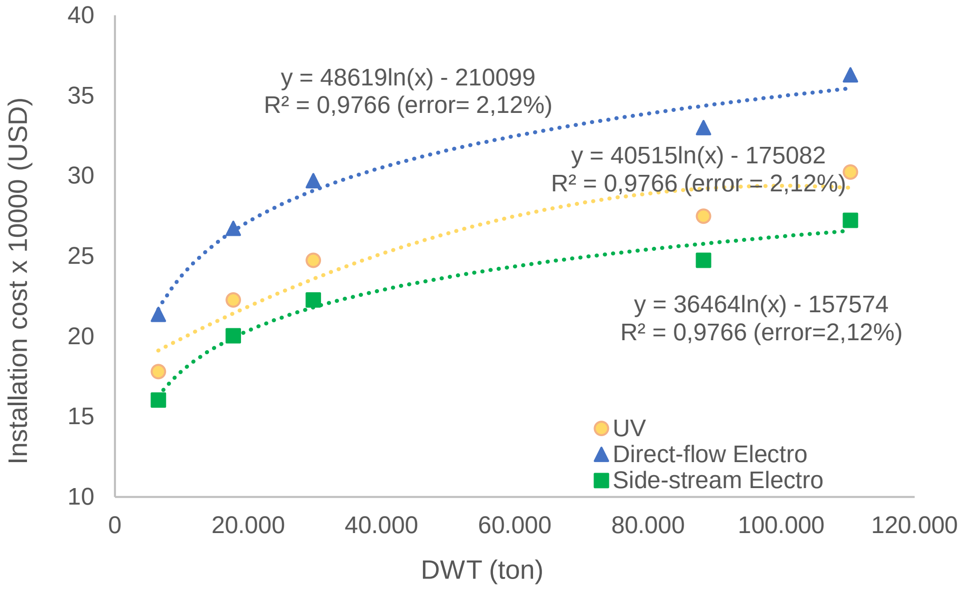

Fig. 6 Correlation of Ship size and installation cost of BWTS technology

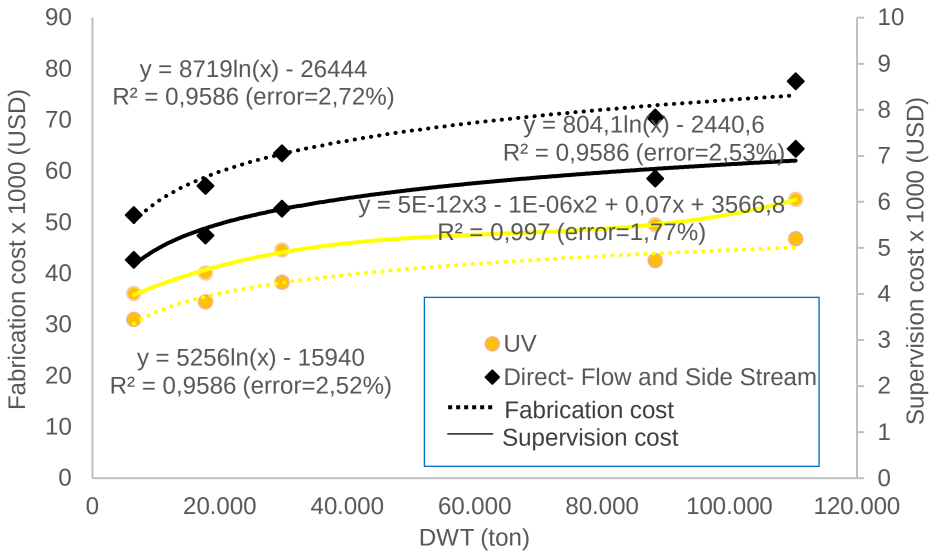

Fig. 7 Correlation of Ship size, fabrication, and supervision cost

The study focuses on retrofitting small tankers and estimate to take 6 to 8 months based on turnkey literature. This simulation uses the maximum duration as the duration of the retrofitting process. The simulation results are analyzed and presented in the results chapter and discussion.

The assumptions used from an expert judgment through interviews with practitioners. The retrofitting process requires a systematic approach to ensure its successful implementation. The following steps outline the procedure below.

- Engineer Selection: The shipowner is responsible for selecting an engineer to conduct a feasibility study. Engineers analyze the retrofitting process and select suitable BWT technology. This stage takes approximately 4 to 6 months and estimates to draw, approve, and detail the ship system. The shipowner pays 70% of the cost as a down payment and pays off the remaining balance upon the engineer's work completion.
- Payment and Equipment Ordering: The shipowner order BWTS technology from a supplier using the draw document. The supplier requires 14 days to prepare each item for shipment. Upon the arrival of the equipment at the shipyard, the shipowner must pay 70% of the equipment price.
- Shipyard Selection and Agreement Payment: The shipowner selects a shipyard for the installation and pays a cost of 40% of the quotation offered. The shipyard starts fabrication after scheduling, which involves constructing and assembling the BWT system. In this stage, the engineer and supplier work together to ensure timely and efficient completion. Additionally, the shipowner should pay 35% of the quotation when the ship is ready for installation. The final payment, following the successful installation and commissioning, settles all outstanding debts related to the retrofitting process. As a result, the ship will be fully operational and ready for use.
- Operation and Maintenance Costs: The ship is deemed ready for operation, and the costs of operation and maintenance are integrated into the model and calculated over the ship's lifetime.

The assumptions and steps above can be integrated into a system dynamics approach. It involves processes with a delay function and outputting accumulated costs at each stage. The supplier incurred the highest costs in the retrofitting process as procurement from the equipment price. The use of delay functions in the model allows for a representation of the payment model in real-world scenarios, even though the costs are expressed in accumulated amounts.

4.2 Result

The application of System Dynamics provides a comprehensive solution for capturing its dynamic elements in the retrofitting process. The Delay function accurately represents the rate of shipowner payments and tracks the amount over time. The simulation results show that the model accurately predicts the retrofitting cost for different BWTS types. The Average Model Error (AME) is around 5-6% for all types, meaning the model is close to the actual costs, and the Average Variance Error (AVE) is also low, around 2%. The confidence level of the retrofitting costs for each ballast water treatment system (BWTS) exceeds 94%, enabling this model to predict additional costs accurately.

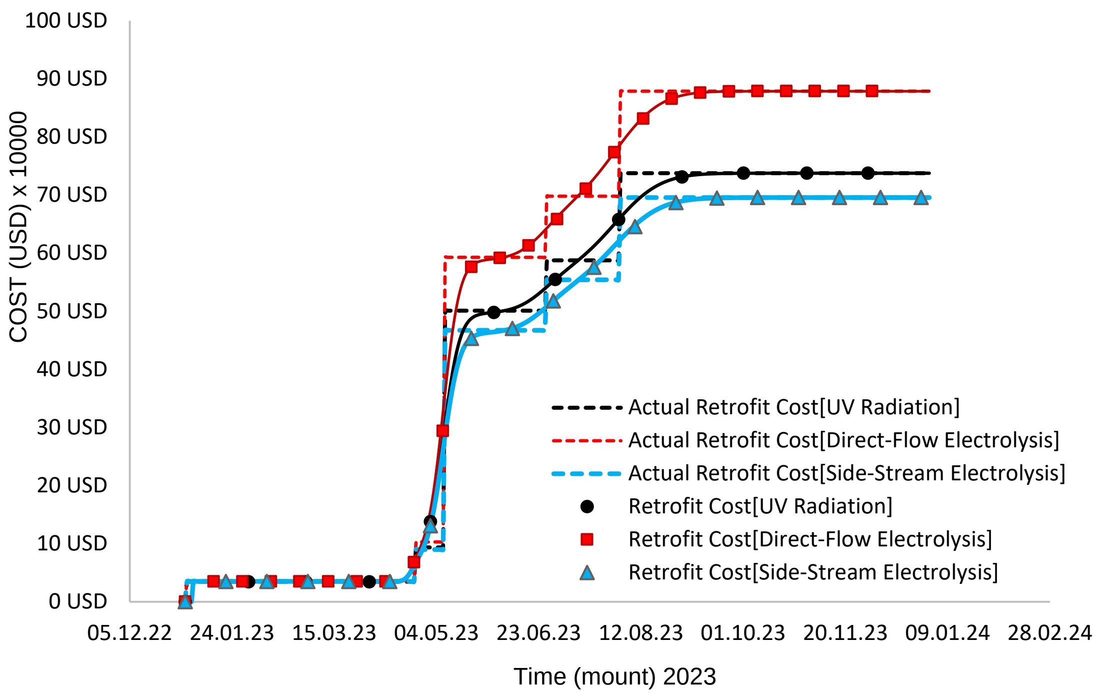

Fig. 8 Comparison of retrofitting cost

This approach is applied to three different BWTS types, with the simulation results accurately matching the actual costs. The model and actual costs are USD 737,765 for BWTS type A, USD 878,867 for BWTS type B, and USD 695,813 for BWTS type C. These results demonstrate the effectiveness of the system dynamics approach in providing an accurate representation of the retrofitting cost, including the payments made by the ship owner over time. The results of the retrofitting cost simulation are presented in Fig. 8, which indicates that BWTS type C has lower retrofitting costs than other technologies. However, the operational costs for the electrolysis method are higher than those for the UV radiation. The operating costs of the BWTS technologies are determined by the power requirements and the use of chemical substances for neutralizing the ballast water before discharge. The UV system has lower operational costs as it does not require neutralizing chemicals. The side-stream electrolysis system has the highest power requirements, leading to the highest operating costs among all the technologies.

The simulation results indicate that type C has lower initial compliance costs than other BWTS technology types, but overall compliance costs will increase over time due to higher operational and maintenance expenses. Type A is a more cost-effective choice after 2029 for this case. The conventional LCC method can not observe the changes in compliance costs over time, hence only recommending type A as the most cost-efficient option. It is determined that for ships with a shorter operating lifetime of fewer than six years, type C is more economical, while for more prolonged operations, type A is the more cost-effective choice.

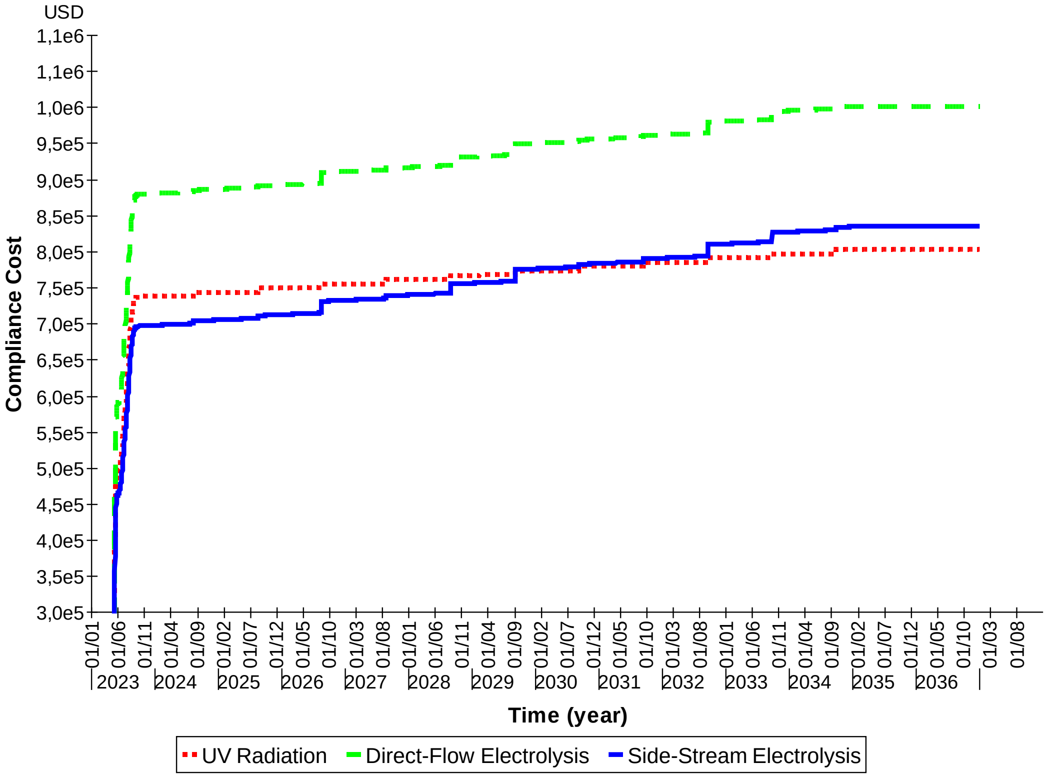

Fig. 9 Compliance costs simulation

The analysis conducted in this result shows that the initial investment cost of BWTS type C is the lowest among others, with a cost of 319,234 USD. Type A is 11% more expensive than type C, while type B is 33% more expensive than type C. It indicates that the initial investment of type C is the most cost-effective option among the three BWTS types for the specific ship. Based on the operating cost, the cost-effectiveness of the BWTS type C's operating cost is 53% greater than that of type A. The result suggests that type C may have a lower initial investment cost but may be less cost-effective in the long run due to its higher operating cost. Overall, these findings highlight the importance of considering the initial investment and operating cost when selecting a BWTS type for a specific ship. While type C may be more cost-effective in terms of initial investment, type A may be a more cost-effective option in the long run due to its lower operating cost.

The simulation results of various BWTS technologies, as shown in Fig. 10, provide valuable information for selecting the most appropriate technology for a specific ship and its operations. It is crucial to consider both the initial cost and the long-term operational expenses of each technology. In addition to these financial considerations, several external factors should also be considered.

- Regulations: The ship's operation must comply with international and national regulations regarding ballast water discharge. It is essential to select a BWTS technology that meets the current regulations.
- Water Quality: The water quality in the area where the ship operates should be considered when selecting a BWTS technology. Some technologies may not effectively treat water with high sediment levels or other contaminants.
- Ship Size and Type: The size and type of the ship should be considered when selecting a BWTS technology. Some technologies may not be suitable for large vessels or specific types of ships.
- Environmental Impact: The environmental impact of the BWTS technology should also be considered. Some technologies may have a lower environmental impact, while others may have a higher impact.

The simulation results provide helpful information for making an informed decision about the best BWTS technology for a specific ship and its operations. However, it is essential to consider the financial and external factors mentioned above to choose the most cost-effective and practical solution. The decision should be based on a comprehensive evaluation of all relevant factors, considering the ship's specific needs and operations.

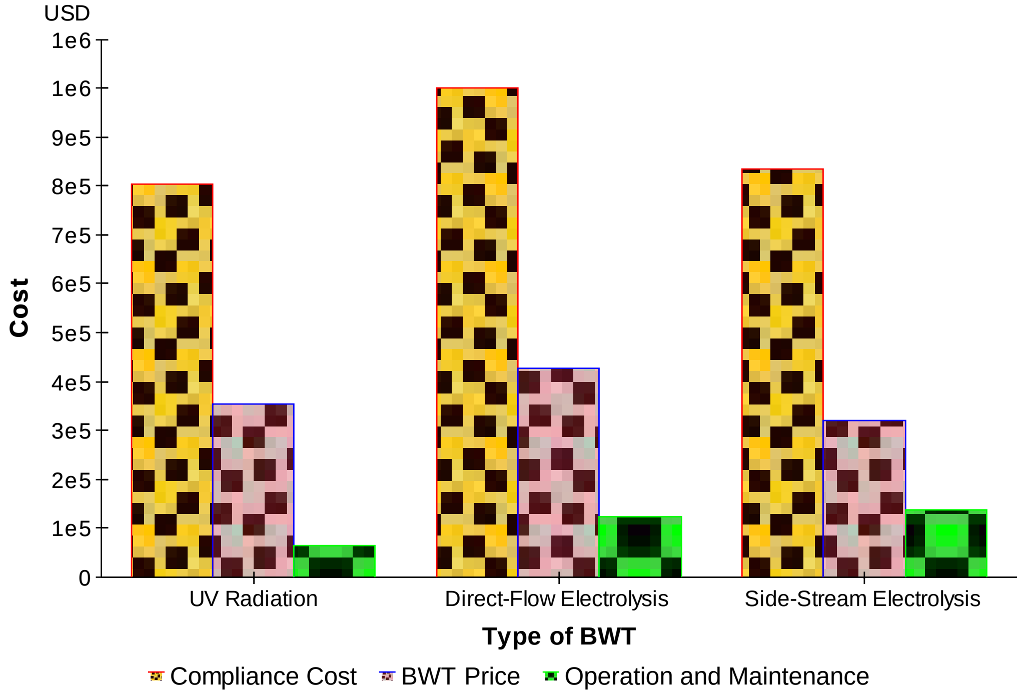

Fig. 10 Cost Comparison of each BWTS technology

5 CONCLUSION

The purpose of the study is to estimate the cost of complying with the BWMC. The model develops considering various factors such as the ship's lifetime, availability of resources, and different BWTS technologies. The model can simulate ship categories such as General Purpose, Handymax, and Aframax based on historical data. The simulation results for the small tanker category case show that BWTS technology type A is the most economical system, costing USD 802,860 for the remaining 12 years of the ship's life. The BWTS technologies type C and type B are 4% and 25% more expensive. It can be a guideline for selecting the most cost-effective BWTS technology for a particular ship and its operations.

However, it is essential to note that selecting a BWTS technology requires a comprehensive study. It considers all relevant factors, such as voyage route, duration, and other factors. This model has some limitations in considering essential variables such as installation difficulty, availability of ship documents, and shipyard performance, which can significantly impact the compliance cost and should be considered in the decision-making process. Therefore, further research is needed to expand the model and make it more comprehensive in selecting a BWTS technology for a specific ship.

In conclusion, this compliance cost model provides valuable insights into the costs of complying with BWMC and helping stakeholders choose appropriate BWTS technology. Further research is needed to expand the model and consider all relevant factors to ensure that the most cost-effective and practical solution is selected for each ship.

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