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**Selçuk Nas**

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Dear Readers,

We are pleased to introduce JEMS 11 (1) to our valuable followers. We are very excited that this issue is the first issue of our second decade. We hope that we will complete many more ten-year periods. In this issue, there are valuable and intriguing studies. No doubt that these studies will contribute to the maritime industry. Hereby, I would like to express our gratitude to the authors, who sent their valuable studies for publication in this issue, our reviewers, editorial board, section editors, and the publisher, who provided quality publications by diligently following our publication policies.

**Yours Sincerely,**

Prof. Dr. Selçuk NAS

Editor in Chief

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# Polygonal Type Fuzzy Ship Domain-Based Decision Support System for Collision Avoidance Route Planning

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## Abstract

This study presents a methodology for a decision support system based on a polygonal fuzzy ship domain, which takes into account the Convention on International Regulations for Preventing Collisions at Sea. A user interface has been created for the decision support function of collision avoidance (CA) at sea by designing a C# form application using the Microsoft Visual Studio platform. Numerical experiments and case scenarios have demonstrated that the proposed model can provide a reasonable and practical solution. Additionally, the results indicate that the developed model can accurately manage the CA action, and the planned CA trajectory can ensure safe navigation. This study is an excellent example of an algorithm structure that combines fuzzy logic and a deterministic approach. The developed methodology is anticipated to effectively guide vessel traffic services operators and navigators and contribute to ship automation, e-navigation strategy, and navigational safety at sea.

**Keywords:** COLREG, Ship domain, Fuzzy logic, Collision avoidance, Optimization

## 1. Introduction

Maritime transportation plays a crucial role in global trade and the world economy. As international trade volume continues to grow, so does the demand for maritime transportation, resulting in more intense and crowded maritime traffic [1]. According to the United Nations Conference on Trade and Development, world maritime trade volume increased by 3.2% in 2021 compared to the previous year [2]. This situation places an even greater burden on navigators and operators and increases the likelihood of maritime accidents. Therefore, a decision support system can help alleviate this burden by assisting navigators and operators in effectively mitigating collision risks during decision-making [3].

In practice, navigators often make subjective decisions regarding collision avoidance (CA) maneuvers, with support from bridge navigational aids, such as electronic chart display and information system (ECDIS), automatic identification system (AIS), and automatic radar plotting aid (ARPA) radar. The ARPA radar is particularly important for assessing collision risks but cannot suggest the best route for CA planning. Likewise, although the trial maneuver mode of radar can provide data on ship movements, it cannot provide information on the best CA maneuvers.

According to Convention on International Regulations for Preventing Collisions at Sea (COLREG), head-on, crossing, and overtaking are the main types of encounters at sea, as shown in Figure 1. Additionally, COLREG identifies and regulates these encounters, as shown in Table 1.

Figure 1 shows different encounter types as other ships approach the ship under our control (OS) from various angles. Each ship has different responsibilities according to COLREG for each encounter. For instance, when the target ship (TS) approaches from an angle between 5° and 112.5° (the light grey area in the figure), the OS is the give-way vessel, and the other ship must maintain its current movement as a stand-on vessel by keeping its course and speed constant.

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*Table 1. COLREG rules for encounter situations*

| Rule | Encounter situation | Own ship (OS) | Target ship (TS) | Rule description |
|---|---|---|---|---|
| R13 | Overtaking | Give-way or stand-on | Give-way or stand-on | "any vessel overtaking any other shall keep out of the way of the vessel being overtaken" |
| R14 | Head-on | Give-way | Give-way | "when two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision, each shall alter her course to starboard so that each shall pass on the port side of the other" |
| R15 | Crossing (dark grey)<br>Crossing (light grey) | Stand-on<br>Give-way | Give-way<br>Stand-on | "when two power-driven vessels are crossing to involve risk of collision, the vessel which has the other on her starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel" |
| COLREG: Convention on International Regulations for Preventing Collisions at Sea | | | | |

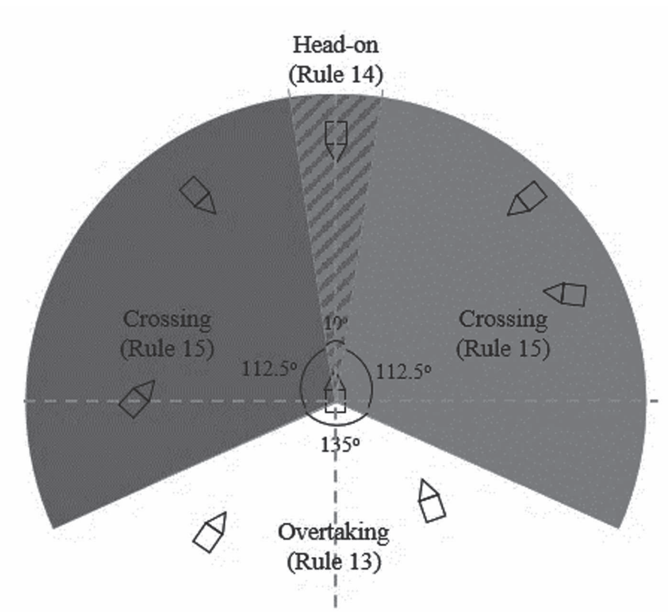


***Figure 1.*** *Encounter situations of ships at sea (OS is on the centre while TS is approaching from different angles)*

The COLREG rules define encounter situations on a one-to-one basis, so this study primarily focuses on such situations and does not consider encounters involving multiple ships. To solve maritime encounter situations and propose the optimal CA route, this study introduces a deterministic-based approach that accounts for the requirements of COLREG. Unlike similar studies in the literature, this methodology uses a polygonal fuzzy ship domain (SD) surrounding the ship for collision risk assessment. Figure 2 depicts the methodological flowchart of the presented approach. Initially, data is gathered from relevant instruments, such as AIS, Global Positioning System, and ECDIS to determine the current state of the encounter situation. The collision risk assessment is then conducted by determining the SD for OS. Next, the relative motion of TS is calculated and checked to see if it violates the SD. If there is a violation, it indicates a risk of collision. In such a scenario, OS, as the give-way vessel, should take evasive

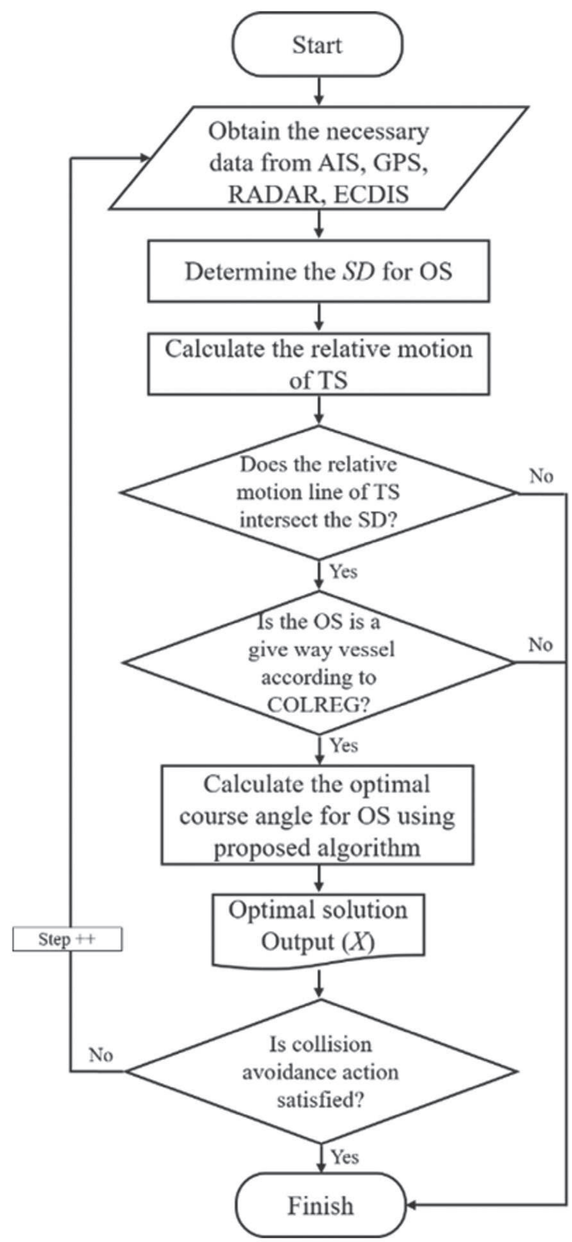


***Figure 2.*** *Methodological flowchart for model development*

action. The proposed model determines the optimal course alteration degree and provides the optimal solution. If the CA action is unsatisfactory, the system reverts to the initial step to improve the solution.

The study is divided into several sections: Section 2 contains a literature review summarizing contemporary works. Section 3 provides information about the model definition of the methodology introduced. Section 4 presents the findings of numerical experiments. Section 5 discusses the study's findings in comparison with other works. Section 6 outlines the limitations of the study. Finally, Section 7 concludes the study and makes recommendations for further research.

## 2. Literature Review

Encounters that involve collision risk are crucial for ensuring navigational safety at sea [4]. Consequently, this topic is one of the most widely discussed areas in the field and is frequently studied by researchers.

Kim et al. [5] have developed a method based on the Distributed Stochastic Search Algorithm (DSSA) that allows for stochastic alteration of a ship's route by detecting the movement intentions of TS. The experimental test results showed that DSSA is more efficient than previously developed distributed algorithms, such as the distributed local search algorithm and distributed tabu search algorithm. The authors suggested that their system takes into account both safety and efficiency.

Liu et al. [6] have introduced a model that offers CA route planning based on the particle swarm optimization algorithm. The model uses the fuzzy quaternion SD to assess the collision risk. Simulation tests were implemented to demonstrate the performance of the model.

It has been shown that the model can effectively address the CA problem. Lazarowska [7] developed another algorithm for route planning using Artificial Potential Field (APF) to suggest a safe route for ships. The author claimed that this model can provide a close-to-real-time solution, taking into consideration obstacles (static and dynamic). Experimental tests were conducted to demonstrate the effectiveness of the model under various scenarios, and the results confirmed its effectiveness.

Fiskin et al. [8] proposed a model based on deterministic features, allowing the vessel to change course deterministically to eliminate the risk of collision using the shortest safe route. The system was tested experimentally and was found to be applicable and outperform Artificial Intelligence (AI)-based methods. Lyu and Yin [9] also presented a deterministic-based method that returns a real-time solution in different environments. In their study, an APF-based system was developed to address encounter situations, including emergencies.

Huang et al. [10] developed an interpretable and interactive CA system for practitioners by modeling the CA process on ships through human-machine interaction. The applicability of the proposed model was supported by scenario tests performed with an Unmanned Surface Vehicle (USV). Zaccone and Martelli [11] introduced a model for CA in open waters based on the Rapidly exploring Random Tree algorithm. The authors stated that the proposed approach was designed to function as the top layer of the control structure of autonomous vessels navigating in open waters. The experimental tests determined that the developed model can plan an unobstructed alternative route and then alter the ship to its original route, avoiding the surrounding obstacles in almost real-time.

Fiskin et al. [12] proposed a CA methodology that utilizes a genetic algorithm (GA) and fuzzy logic. The methodology included qualitative and quantitative research processes and was experimented with in a virtual environment using a bridge simulator and in the real environment with a USV through different scenario cases. The authors stated that the algorithm produced satisfactory findings and can be used as a CA submodule within the navigation module for unmanned ships and USVs.

Li et al. [13] introduced a CA route planning methodology based on deep reinforcement learning to solve the safe trajectory planning problem of autonomous surface vehicles in uncertain environments. In the developed model, the environment of the TS was divided into four level avoidance zones, and a risk assessment was carried out according to these zones. Simulation experiments were planned to test the effectiveness of the model in various environments. The experiments showed that CA route planning could be performed effectively with the model.

Szlapczynski and Szlapczynska [14] presented a novel model for collision risk assessment for near-miss detection, which mainly uses a SD concept. A total of five variables were used such as relative speed of vessels, encounter complexity, and arena violations. Additionally, case studies were provided to verify the system's suitability. The authors highlighted that the presented system deals tremendously well with early maneuvers.

Zhao et al. [15] developed an intelligent model for CA in open waters, which takes into account the ship's maneuverability. The model combines the mathematical modeling group (MMG) approach with a three-degree-of-freedom maneuvering model in various environmental conditions, taking into consideration the ship propeller characteristics. The algorithm ultimately decides to change the course and/or speed of the ship. The proposed model was tested through simulation with various scenarios. The findings showed that the optimum CA action can be achieved with the decision made by the system. Du et al. [16] introduced a collision warning system based on the risk perception of the navigator to initiate a timely CA maneuver. The proposed system was tested with various encounter cases, showing its feasibility in both one-to-one and multi-ship encounter situations. García Maza and Argüelles [17] aimed to identify and classify basic criteria for decision-making in ship encounters with respect to COLREG. The authors offer insights into ship CA considering COLREG.

In conclusion, the problem of CA route planning is a hot topic that attracts the interest of researchers. Many approaches to the solution of the problem have been introduced so far. Some recent studies, detailed in Table 2, are provided in the previous paragraphs. It is revealed that the SD is commonly used for collision risk assessment in most studies. Similarly, this study uses the SD method for collision risk assessment. However, unlike most studies, which generally use a circular or elliptical SD, a polygonal SD is used in this study. The proposed model in this study also has a deterministic algorithm structure in addition to a polygonal SD with a fuzzy structure. Since no similar approach exists in the literature, this study fills the gap in the related field.

## 3. Materials and Methods

SD, traffic flow theory, and closest point of approach are methods in the literature used for collision risk assessment [18]. If a vessel violates the free area of another vessel in the vicinity, it is considered at risk of collision, and the give-way vessel should take CA action [19,20]. SD is defined as “the area surrounding a ship where a navigator aims to keep free with respect to other ships or obstacles” [21]. Although the circular SD is commonly used in practice, this study utilizes a polygonal, fuzzy SD (as illustrated in Figure 3 and introduced by Fiskin et al. [20]) for collision risk assessment.

The introduced model has several advantages. The size and shape of the domain are determined by expert interviews and literature, taking into account factors that affect them:

a) ship length (L),

b) ship speed (V),

c) maneuverability (M),

d) traffic state (T),

e) navigator experience (N),

f) daytime (daylight or night) (D),

***Table 2.*** *Current models proposed by various authors*

| Reference | Approach type | Action type | Risk assessment method | Domain type | Complex environment | Method type | Obstacle characteristic |
|---|---|---|---|---|---|---|---|
| Kim et al. [5] | AI | Route change | Ship domain | Circular (around the OS) | Yes | DSSA | Dynamic |
| Liu et al. [6] | Deterministic | Route change | Ship domain | Elliptic (around the OS) | No | Analytical | Dynamic |
| Lazarowska [7] | AI | Route change | Ship domain | Hexagon (around the TS) | Yes | APF | Dynamic |
| Fiskin et al. [8] | Deterministic | Route change | Ship domain | Circular (around the OS) | No | Analytical | Dynamic |
| Lyu and Yin [9] | AI | Route change | Ship domain | Circular (around the OS) | Yes | APF | Dynamic |
| Huang et al. [10] | Deterministic | Route/speed change | - | - | Yes | Analytical | Dynamic |
| Zaccone and Martelli [11] | AI | Route change | Ship domain | Circular (around the OS) | Yes | RRT | Dynamic |
| Fiskin et al. [12] | AI | Route change | Ship domain | Circular (around the OS) | No | GA, fuzzy logic | Dynamic |
| Li et al. [13] | AI | Route change | Ship domain | circular (around the OS) | No | DRL | Dynamic |
| Szlapczynski and Szlapczynska [14] | Deterministic | Route change | Ship domain | Elliptic (around the OS) | Yes | Analytical | Dynamic |
| Zhao et al. [15] | Deterministic | Route/speed change | Ship domain | Elliptic and circular (around the OS) | Yes | MMG | Dynamic |
| Du et al. [16] | Deterministic | Route change | Ship domain | - | Yes | Analytical | Dynamic |
| Proposed model | Deterministic | Route change | Ship domain | Polygonal (around the OS) | No | Analytical | Dynamic |

g) sea state (W),

h) visibility (I),

ı) relative bearing (RB) of the TS (E).

Their values were defined based on literature. For instance, ClassNK and Kao et al. [22] analyzed ship length using AIS data, while ship speed was determined by considering the ship speed categorization in the ITU-R M 1371-1 report [23]. Additionally, the navigator's experience was taken into account by considering the promotion periods in Türkiye.

The aim of the CA route maneuver is to keep the SD clear of other ships or objects. To optimize this maneuver, the relative motion vector of the TS should be tangential to the SD. The algorithm outlined below is introduced to determine the course degree (X) that will provide the optimal maneuver.

1. Setting of initial values;
- $f(a,b) = \overrightarrow{(Cos(a) * b, Sin(a) * b)}$
- $U = C_{os(initial)}$
- $L = C_{os(initial)} - 180$

2. For IC times;
- $C = (U + L)/2$
- $\vec{S} = f(C, |\overrightarrow{V_{os}}|)$
- $\overrightarrow{RS} = \overrightarrow{V_{ts}} - \vec{S}$
- $d = C - C_{os(initial)}$
- $cTheta = Cos(d)$
- $sTheta = Sin(d)$
- For every point $\vec{P_i}$ in SD
  - $cTheta = Cos(C - C_{os(initial)})$
  - $\vec{P_i'} = \overrightarrow{cTheta * \vec{P_i}.x - sTheta * \vec{P_i}.y, sTheta * \vec{P_i}.x + cTheta * \vec{P_i}.y}$
- If a ray starting from a point $\overrightarrow{P_{ts}}$ and has the same degree with $\overrightarrow{RS}$ **intersects*** SD:
  - Then:
    - $L = C$
  - Else:
    - $U = C$
- Repeat step 2

3. $U_{final} = U$

**BigOh (*IC* * Intersection Check)**

$U_{final}$ refers to the final value for the optimal avoidance course. The $U_{final}$ error for optimum degree $X$ is determined by Equation 1:

$$|X - U_{final}| \leq {}^{180}/_{2^{IC}} \quad (1)$$

where $U$ denotes the upper course bound, $L$ denotes the lower course bound, denotes the initial course of the OS, $C$ represents course on check, $IC$ denotes the iteration count, denotes the relative speed vector, denotes the position vector of the TS, $SD$ denotes the SD of the OS, and $P_i$ denotes the $i$. point in SD. is the OS speed vector which includes magnitude and course components of the OS speed.

*The following algorithm is applied to control the intersection of ray and polygon:

### Intersection Check:

1. For every two consecutive points P1 and P2 in polygon SD

- If ray **crosses between**** P1 and P2:
  - Then ray intersects safety SD
  - Return.

2. If ray does not cross between any consecutive points:

- Then; ray does not intersect safety SD
- Return.

**The following algorithm is applied to determine if a ray, starting from point $O$ and moving toward $M$, crosses between two points $P1$ and $P2$:

### Crossing Check:

A = P1,B = P2,C = O,D = M ➔

1. a1 = B.y - A.y
2. b1 = A.x - B.x
3. c1 = a1 * (A.x)+ b1 * (A.y)
4. a2 = D.y - C.y
5. b2 = C.x - D.x
6. c2 = a2 * (C.x) + b2 * (C.y)
7. d= a1 * b2 - a2 * b1
8. If d= 0

- Then:
  - Ray does not cross between P1 and P2
  - Return.
- Else
  - x = (b2 * c1 - b1 * c2) / d
  - If ((x < A.x and x > B.x) or (x > A.x and x < B.x))
    - Ray crosses between P1 and P2
    - Return.

9. Ray does not cross between P1 and P2
10. Return.

## 4. Numerical Experiments

In numerical experiments, the results of the proposed model were observed under various scenarios, taking into account different ship encounter types, such as head-on, crossing, and overtaking. A practical user interface was created for the decision support function of CA at sea using a form application designed in the C# programming language on the Microsoft Visual Studio platform. As shown in Figure 3, the left side of the interface displays inputs provided by the system user and the SD produced by the system based on these inputs. The right side shows the spatial operation and simulation of ship motions. In the simulation, the SD of the OS represented by the green area should not be violated by other objects, and the blue line refers to the optimal trajectory suggested by the system for the OS. Experimental studies were conducted using a personal computer with an Intel(R) Core(TM) i7-9700 3.00Ghz processor and 8GB RAM. The scenario inputs of the numerical experiments and the results obtained from the scenarios are presented in Tables 3 and 4, respectively.

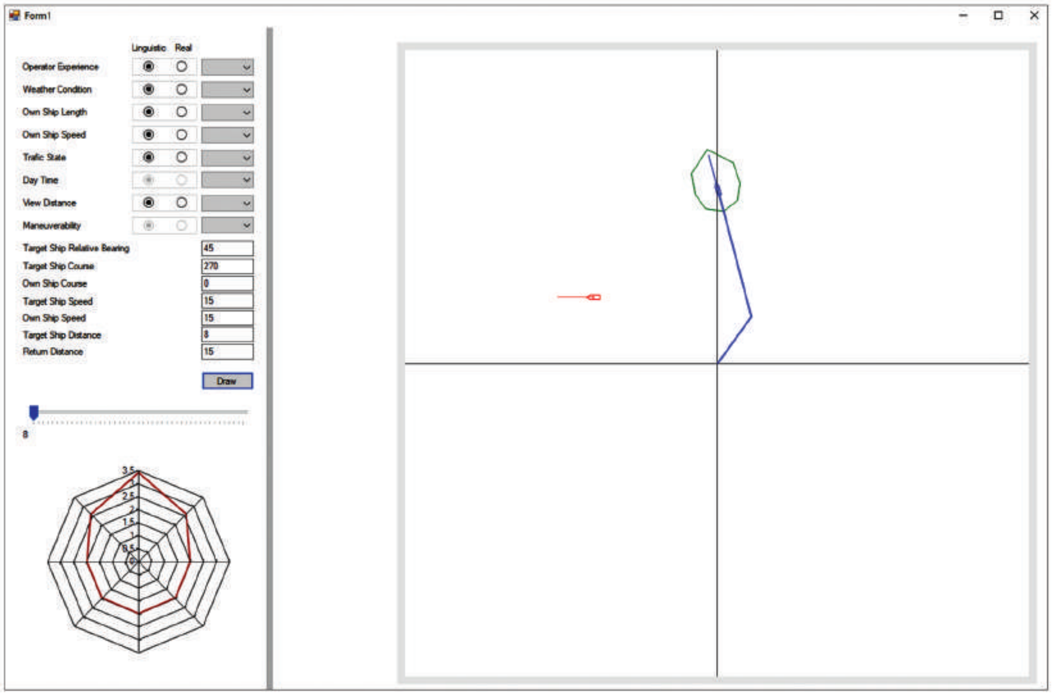


***Figure 3.*** *User interface (OS and TS represent with blue and red, respectively)*

### 4.1. Case 1: Head-on Situation

In Case 1, TS and OS approach each other on opposite courses. The initial course of OS ($\Phi_{OS}$) is 000°, while TS's course ($\Phi_{TS}$) is 180°. OS's speed (V) is 15 knots, and TS's speed ($V_{TS}$) is 10 knots. The RB of TS (E) is 5° to starboard, and the distance of TS to OS (TSD) is 15 nm. For this experiment, the 8-node approximation is used for the SD.

The following input values are set for the SD: OS's length (L) is 150 m, OS's speed (V) is 15 knots, OS's maneuverability (M) is medium, traffic state (T) is low, navigator experience (N) is 6 years, daytime (D) is night, sea state (W) is 2 forces, and visibility (I) is at least 12 nm. In this case, the optimal CA action is for the OS to change course from 028° to starboard, according to these input variables. Figure 4 shows the ships' movements that occurred in Case 1.

### 4.2. Case 2: Crossing Situation

In Case 2, TS is located on the starboard bow of OS. The parameters in this scenario are $\Phi_{OS}$ at 000°, $\Phi_{TS}$ at 260°, V at 12 knots, $V_{TS}$ at 15 knots, E at 35° starboard, and TSD at 15 nm. For this experiment, the 12-node approximation of the SD is utilized.

The following input values are set for the SD: L is 200 m, V is 12 knots, M is high, T is medium, N is 10 years, D is daylight, W is 3 forces, and I is at least 10 nm. As per these input variables, the optimal CA action for OS is to change her course to starboard by 031°. Figure 5 depicts the movements of the ships in Case 2.

### 4.3. Case 3: Overtaking Situation

In Case 3, the OS is located at the stern of the TS. $\Phi_{OS}$ is set at 000°, $\Phi_{TS}$ at 000°, with a speed of 19 knots for V and 6 knots for $V_{TS}$. E is positioned at 2° starboard, and TSD is at 3 nm. The experiment utilizes the 16-node approximation of the SD.

For the SD input values, L is set at 120 m, V at 19 knots, and both M and T are low. N is set at 8 years, with D in daylight and W at 5 forces. I is set to a minimum of 11 nm. Thus, in this case, the optimal CA action is for the OS to change course 048º to starboard. Figure 6 displays the ships' movements observed in Case 3.

## 5. Evaluation of Results and Discussion

The discussion section of an academic paper is crucial for presenting the performance of the developed model. In this regard, this section aims to practically compare the proposed model with other existing models. Various scenarios have been created to implement the comparison. For comparing AI-based models, the models presented by Tsou et al. [24] and Fiskin et al. [12] have been utilized, while the models presented by Lazarowska [25] and Fiskin et al. [8] have been used for comparing deterministic-based models with different parameter settings, as provided in Table 5. Furthermore, Table 6 and Table 7 present the findings of the comparison and details of the models used for discussion, respectively.

***Table 3.*** *Scenario inputs of the numerical experiments*

| | | | Navigational data | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Ship domain input | | | | | | | | | Collision avoidance route input | | | | | Output |
| | | Encounter type | L [m] | V [kn] | T [ship] | N [year] | W [force] | I [nm] | E [°] | M [γ] | D [γ] | $\Phi_{OS}$ [°] | $\Phi_{TS}$ [°] | $V_{TS}$ [kn] | TSD [nm] | RD [nm] | $\Delta\Phi_{OS}$ [°] |
| Case | 1 | Head-on | 150 | 15 | 3 | 6 | 2 | 12 | 5 | Medium | Night | 000 | 180 | 10 | 15 | 15 | 028 |
| | 2 | Crossing | 200 | 12 | 6 | 10 | 3 | 10 | 35 | High | Daylight | 000 | 260 | 15 | 10 | 10 | 031 |
| | 3 | Overtaking | 120 | 19 | 2 | 8 | 5 | 11 | 2 | Low | Daylight | 000 | 000 | 6 | 3 | 7 | 048 |

***Table 4.*** *Scenario outputs of the numerical experiments*

| | | Encounter type | CA route leg length 1 [nm] | CA route leg length 2 [nm] | CA route total length [nm] | CA course change [°] | Course change to back original route [°] |
|---|---|---|---|---|---|---|---|
| Case | 1 | Head-on | 9.27 | 6.13 | 15.40 | 028 | (-)027 |
| | 2 | Crossing | 5.18 | 5.36 | 10.54 | 031 | (-)037 |
| | 3 | Overtaking | 3.84 | 4.13 | 7.97 | 048 | (-)057 |

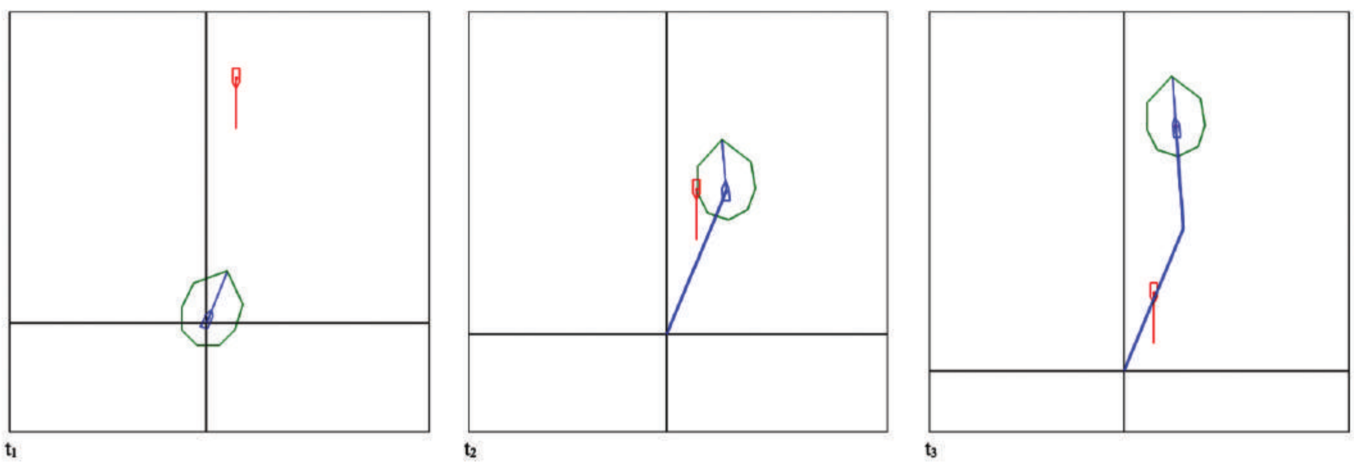


***Figure 4.*** *Collision avoidance action of the OS in Case 1*

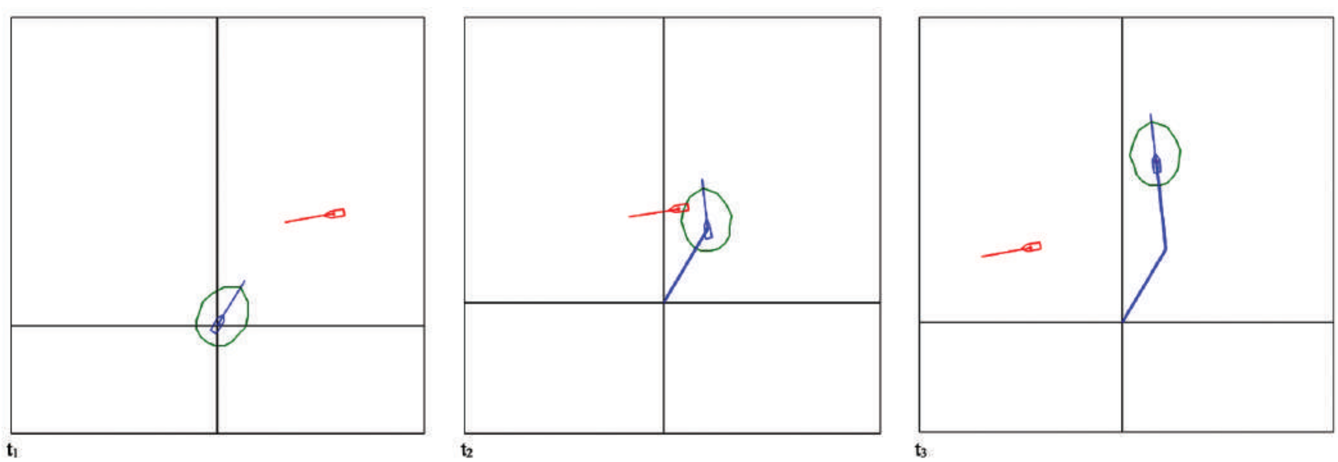


***Figure 5.*** *Collision avoidance action of the OS in Case 2*

### 5.1. Numerical Comparison with AI-based Models

In Case 1, the GA-based model developed by Tsou et al. [24] is compared with the model developed in this study. The CA trajectories formed by both models are shown in Figure 7a. In the comparison scenario, the navigational input data for ships and numerical results provided by both models are shown in Tables 5 and 6, respectively. The table clearly shows that the proposed model outperforms the GA-based model in terms of total CA trajectory length and computational time. In addition, the proposed model produces considerably shorter CA trajectories and has a much shorter computational time, with the advantage of being deterministic. On the other hand, Tsou et al. [24] used a SD radius of 2 nm. To ensure a fair comparison, inputs for a polygonal SD are provided to produce a 2 nm radius for the longest node. An 8-node approximation is used in the polygonal SD.

In Case 2, the solution generated by the proposed model is compared with the solution computed by the GA and fuzzy logic-based model developed by Fiskin et al. [12]. The CA trajectories created by both models are shown in Figure 7b. In the comparison scenario, the navigational input data for ships and numerical results provided by both models are shown in Tables 5 and 6, respectively. The proposed model reaches the solution much faster. Moreover, Figure 7b shows that the trajectory computed by the proposed model is slightly shorter than the one generated by the other model. Fiskin et al. [12] used a circular domain with a radius of 2 nm. To facilitate the comparison, inputs for a polygonal SD are provided to produce a 2 nm radius for the longest node. Similar to the previous case, an 8-node approximation is used in the polygonal SD.

### 5.2. Numerical Comparison with Deterministic-Based Models

In Case 3, a comparison was made between the proposed model and the deterministic method known as TBA, developed by Lazarowska [25]. The CA trajectories generated by the model developed by Lazarowska [25] and the proposed model are shown in Figure 7c. In the comparison scenario, navigational input data for ships and numerical results provided by both models are shown in Table 5 and Table 6, respectively. The comparison revealed that both models produced similar results, except that the proposed model maneuvered a little later to return to the original route. Lazarowska [25] used a hexagonal SD with the longest diagonal line measuring 1.25 nm. To ensure an accurate comparison, inputs of polygonal SD were provided to produce the smallest size, which is approximately 1.5 nm. In this case, a 16-node approximation was used in the polygonal SD.

In Case 4, the results achieved by the proposed model were compared with another deterministic model called the

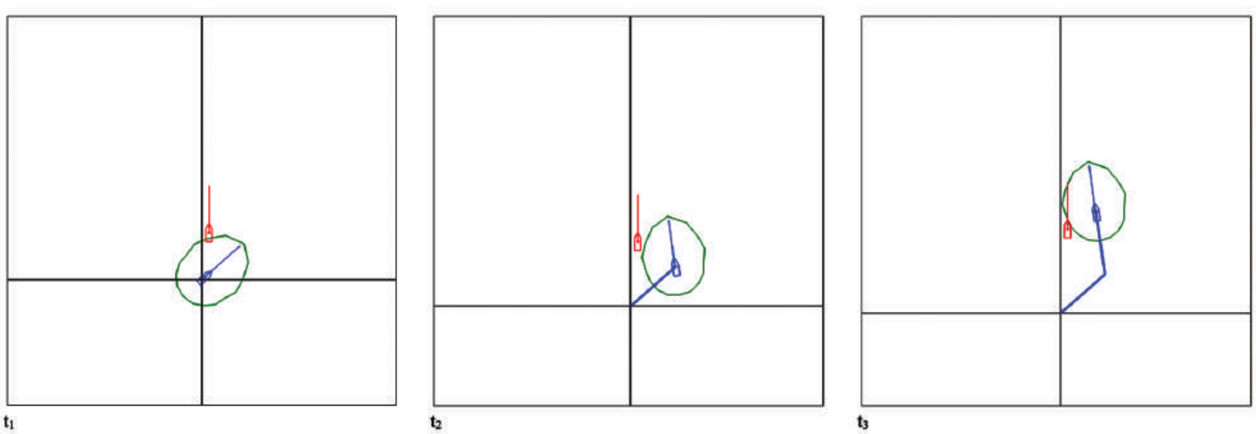


***Figure 6.*** *Collision avoidance action of the OS in Case 3*

***Table 5.*** *Navigational data of ships for comparison scenarios*

| | | | | Navigational input data of ships | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Comparison with | Encounter type | $\Phi_{OS}$ [°] | $\Phi_{TS}$ [°] | V [kn] | $V_{TS}$ [kn] | E [°] | TSD [nm] | RD [nm] |
| Case | 1 | Tsou et al. [24] | Crossing | 000 | 240 | 14 | 15 | 30 | 4 | 3.8 |
| | 2 | Fiskin et al. [12] | Crossing | 000 | 240 | 14 | 15 | 30 | 4 | 3.4 |
| | 3 | Lazarowska [25] | Head-on | 000 | 180 | 14 | 12 | 0 | 8 | 9 |
| | 4 | Fiskin et al. [8] | Head-on | 000 | 180 | 15 | 15 | 0 | 10 | 8.14 |

***Table 6.*** *Numerical results of comparison scenarios*

| | | Method | CA course change [°] | Course change to back original route [°] | Total CA route length [nm] | Computational time [sec] |
|---|---|---|---|---|---|---|
| Case | 1 | Proposed model | 034 | (-)069 | 4.62 | 0.3 |
| | | Tsou et al. [24] | 046 | (-)093 | 5.55 | 14 |
| | 2 | Proposed model | 034 | (-)078 | 4.38 | 0.3 |
| | | Fiskin et al. [12] | 058 | (-)088 | 4.53 | 6.8 |
| | 3 | Proposed model | 013 | (-)026 | 9.23 | 0.3 |
| | | Lazarowska [25] | 014 | (-)025 | 9.22 | 0.4 |
| | 4 | Proposed model | 012 | (-)034 | 8.49 | 0.3 |
| | | Fiskin et al. [8] | 028 | (-)057 | 9.39 | 0.3 |

***Table 7.*** *The discussion of models utilized for comparison*

| Reference | Tsou et al. [24] | Fiskin et al. [12] | Lazarowska [25] | Fiskin et al. [8] | Proposed model |
|---|---|---|---|---|---|
| Method | GA | ColAv_GA | TBA | WBDA | Polygonal-based CA |
| Approach type | AI | AI | Deterministic | Deterministic | Deterministic |
| Type of maneuver | Course change | Course or/and speed change | Course change | Course change | Course change |
| Number of maneuvers | Single | Single | Single | Single | Single |
| Static obstacle | Not Considered | Considered | Considered | Considered | Considered |
| Dynamic obstacle | Considered | Considered | Considered | Considered | Considered |
| Ship domain type | Circular | Circular | Hexagon | Circular | Polygonal |
| Ship domain holding | Around the OS | Around the OS | Around the TS | Around the OS | Around the OS |
| Ship domain characteristic | Static | Static | Static | Static | Static |
| Expression of domain | Safety domain | Ship domain | Ship domain | Ship domain | Ship domain |
| Safety indicator | Violation of the domain | Violation of the domain | Violation of the domain | Violation of the domain | Violation of the domain |
| Objective function | Minimize the CA route length | Minimize the CA route length | Minimize the CA route length | Minimize the CA route length | Minimize the CA route length |
| TS motion | Keeps movement | Keeps movement | Keeps movement | Keeps movement | Keeps movement |
| Action range determination to the TS | No | Yes | No | No | Yes |
| Speed change option | No | Yes | No | No | No |

Web-Based Deterministic Algorithm (WBDA), developed by Fiskin et al. [8]. The CA trajectories provided by the model developed by Fiskin et al. [8] and the proposed model are shown in Figure 7d. In the comparison scenario, navigational input data for ships and numerical results provided by both models are shown in Table 5 and Table 6, respectively. The table clearly shows that the result returned by the proposed model outperformed the WBDA-based model in terms of total CA trajectory length. The time to reach a solution, on the other hand, is about identical since both have deterministic features and can reach a result quickly.

### 5.3. Evaluation of Discussion

In summary, the proposed model is advantageous due to its deterministic nature, allowing for faster results than AI-based models. Additionally, deterministic methods produce consistent results in every execution. The numerical analysis demonstrates that the proposed model outperforms AI-based models, producing shorter CA trajectories in less time. Comparing the proposed model to other deterministic-based methods, it is almost identical in terms of total CA trajectory length and computational time, with the exception of a slight difference in trajectory length when compared to the WBDA model.

## 6. Limitations and Further Improvements

Despite the results and advantages mentioned above, the developed model still has certain limitations. Therefore, additional work is required to enhance the research in the following areas:

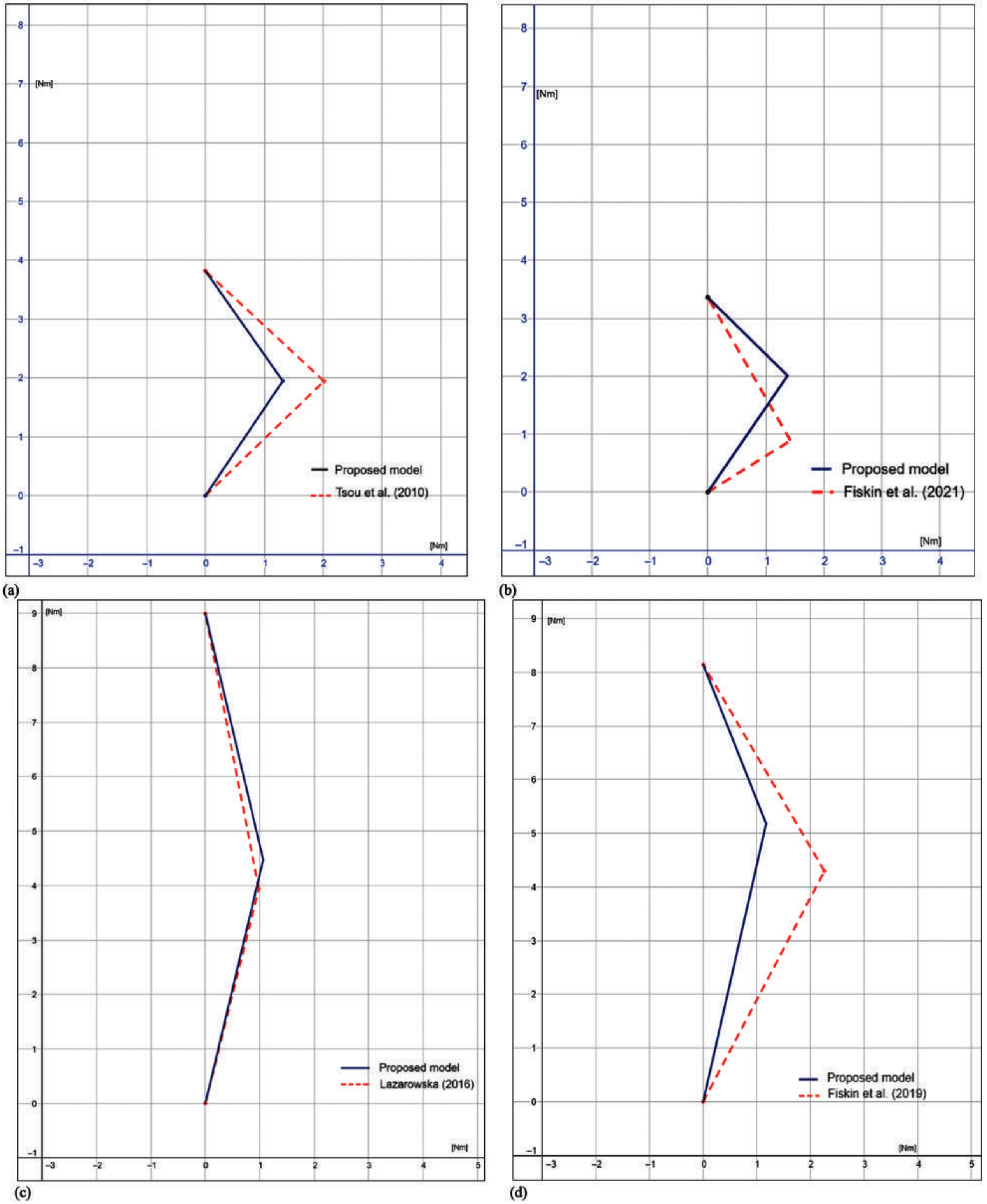


*Figure 7. CA trajectories of the OS obtained by the models in comparison*

- Variations in the motion of the TS are not considered, and it is assumed that it will maintain its current speed and course. However, if a change in course or speed is detected, recalculations must be made based on the new navigational data.

- This model is not intended for complex environments or encounters with multiple ships. Calculations should be made for each ship individually, based on its distance from the OS.

- The calculation of ship movements uses a kinematic model that does not take external forces into account.

- Speed and time losses that occur during ship turns are disregarded.

## 7. Conclusion

In this study, we have developed an optimal methodology for CA route planning in sea navigation, taking into consideration the COLREG rules. Our methodology involves conducting a collision risk assessment with a polygonal-type fuzzy SD. Our numerical experiments demonstrate that our system can generate a sensible solution for ship CA problems. Furthermore, our system has a deterministic algorithm structure, ensuring that it produces the same solution with each execution.

Our CA maneuver is limited to course change and does not take into account speed change. We have excluded speed change from the scope of this study since it is not frequently used to avoid collision in practical situations, except in critical or emergency circumstances. Furthermore, due to the nature of the COLREG rules, we have only considered one-on-one situations. For future research, our system can be designed and adapted for multiple ship encounters, and we can also incorporate other polygonal approximations of the SD to extend the proposed strategy. The findings from this study have the potential to contribute to ship automation and e-navigation strategy.

**Peer-review:** Externally and internally peer-reviewed.

### Authorship Contributions

Concept design: Data Collection or Processing: Analysis or Interpretation: Literature Review: Writing, Reviewing and Editing: All authors have contributed equally.

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# Modeling and Analysis of Container-Type Ship's Marine Propeller for Engine Load Conditions

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## Abstract

Engine room simulators have become increasingly important in practical marine engineering training and education. To ensure their usefulness in both training and academic studies, it is essential to accurately model, simulate, and validate ship propulsion systems within these simulators. This study outlines the design and development of a marine propeller and its hydrodynamic performance analysis using computational fluid dynamics (CFD). To obtain sampled ship and propulsion parameters, a large container-type vessel model in an existing engine room simulator was employed. This study includes the design and development of a new efficient propeller and its propulsion data, which can be used in the development of an engine room simulator. This study demonstrates a methodology for developing training simulators that involve using complex and extensive mathematical modeling. The ship's geometry was designed using 3D modeling software such as Rhinoceros and Maxsurf. To determine the required thrust at each of the main engine's loading modes, the ship's resistance computations were conducted using Maxsurf's HullSpeed module. The authors also developed a MATLAB code to obtain the ship's power requirements. The ship resistance and thrust requirements data were then used as input to design the propeller, and CFD analyses were conducted for the defined engine load conditions. The hydrodynamic performance coefficients of the newly designed propeller were computed, and the CFD results were compared with the existing propeller's performance data. The resulting propulsion data presents the performance parameters for each predefined engine load condition. The analysis demonstrated that a more efficient marine propeller was designed, providing more thrust (up to 9% for a specific mode) while consuming less power compared with the existing one.

**Keywords:** Propeller design, Container ship, Computational fluid dynamics, Engine load conditions, Engine room simulator

## 1. Introduction

Since the publication of Standards of Training Certification and Watchkeeping (STCW) by the International Maritime Organization in 1995, using engine room simulators (ERSs) has become mandatory in maritime education and training [1]. Maritime institutions worldwide employ ERS for training purposes at both operational and management levels, as outlined in this standard document [2-4]. The first section of this study provides a background on the use of an ERS to demonstrate the level of acceptance of this mandatory training tool in maritime institutions and introduces the design and analysis of a propulsion system for a maritime simulator.

Studies have shown that simulation tools for maritime application and design have yielded positive results [5,6]. However, using ERS in propeller modeling is still uncommon. Martelli and Figari [7] conducted a similar study; they designed and modeled the propulsion system of a warship and compared the findings with sea-trial data, but did not provide any data on the engine torque and propulsion power relationship. Such resulting data is important for use in the ERSs to reduce the use of computer resources while continuously calculating and presenting the parameters that are based on the dynamically changing affecting conditions.

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### 1.1. Engine Room Simulator Applications

There have been numerous publications in the literature on the application of marine engine simulators. For instance, Jianyuan [8] conducted a simulation study on a 6-cylinder, Maschinenfabrik Augsburg-Nürnberg AG (MAN) marine diesel engine, comparing the results with data obtained from the same type of engine. Theotokatos [9] employed two different simulation approaches to study a 9-cylinder MAN-type marine diesel engine and compared the results of both approaches. ERS is mainly designed to train engineering cadets for operational and management level competencies, as specified in IMO STCW 2010 [10]. IMO Model Course 2.017 [11] also outlines the exercises necessary to achieve these competencies. Simulator-based training offers several advantages in the field of marine engineering and technology. ERS has been recognized as a valuable tool for training and evaluating seafarers [12]. Academic publications also contribute to improving ERS exercises and offer a comprehensive understanding of how ERS can be employed in various design, training, and educational studies. Mangga et al. [13] showed how ERS could be used to assess the performance of students. Zaini [14] studied the effectiveness of ERS as a learning tool in maritime education and training. Chybowski et al. [15] provided several examples of ERS usage as a tool for explosion and fire prevention training. Kojima et al. [16] designed ERS scenarios for engine room resource management training, while Kluj [17] emphasized the importance of the environmental awareness concepts in ERS training. In addition to being mandatory in accordance with international agreements [10], the wide range of publications are available on ERS demonstrating its acceptance as a tool for maritime education and training worldwide. This is further evidenced by the fact that a Google Scholar search for the keywords “Engine Room Simulator” and “Training” yielded 220 results related to the topic.

Another area in which simulators are used is in understanding the behavior and performance of ship engines, propulsion systems, and in the design and demonstration of models and analysis studies. Seddiek [18] examined engine performance and simulated various processes to demonstrate how ship performance and energy management could be improved. Seddiek’s [18] findings demonstrated that emissions and fuel consumption could be reduced using different operational methods. Yutuc [19] studied the overall efficiency of ships by incorporating a shaft generator. There are also publications detailing the partial or complete development of ERS. Weifeng et al. [20] designed a model to simulate a hydraulic steering gear system. Shen et al. [21] presented an educational virtual reality training system that enables students to understand the working principle of marine engineering systems and enhance their practical ability skills more efficiently. Rubio et al. [22] developed and presented a marine diesel engine failure simulator based on a thermodynamic model. Jung et al. [23] generally described the development of a marine ERS for use in training and research.

### 1.2. Engine Room Simulator and Propulsion

The aforementioned publications were presented as examples of ERS development; however, the authors of this study could not find a publication on the development of an ERS that describes the propulsion system design and analysis and how propulsion modeling has been introduced in an engine room training simulator. Although the field of propulsion systems studies is extensive, there is a lack of information regarding the integration of analysis results into ERS. When developing simulators, propulsion parameters must be estimated using either a modeling and analysis approach or test data that can be correlated to match the simulation algorithms. For instance, Altosole and Figari [24] developed a propeller system simulation using the torque and power parameters of the main engine. Karlsen [25] modeled a propulsion system for control system development. Özsari [26] conducted a thermodynamic performance analysis for a submarine propulsion system. Similarly, Chavez et al. [27] modeled three propulsion systems for a fishing vessel to model and simulate the Sunkey diagram. In this study, the method to develop a propeller and analyze the propulsion system for the engine load conditions with respect to each of the speed, or revolutions per minute (RPM), which was employed for a containership, as described in Section 2 Methodology.

### 1.3. Modeling & Analysis of Ship Propulsion Systems

The analysis and modeling of a ship’s propulsion system are crucial in determining the performance, reliability, and efficiency of ships in shipping operations. The primary components of the propulsion system, propellers, can be modeled and analyzed using various methods, including lifting line, lifting surface, and Computational Fluid Dynamics (CFD) approaches [28]. Although in the past, numerical approaches such as lifting surface and boundary element approaches have been preferred for propeller design and hydrodynamic performance computations of marine propellers, CFD approaches have become more common due to the recent technology developments with high computer performance capacities.

Numerous publications have reported the analysis of marine propellers using CFD computations. Rhee and Joshi [29] simulated the flow around a marine propeller using the Reynolds-averaged Navier-Stokes equations (RANS equations) and compared the CFD findings with experiments, showing good agreement in terms of propeller thrust and torque values. Kulczyk et al. [30] examined a David Taylor Model Test Basin (DTMB) standard propeller using the RANS approach with k-ε and k-ω turbulence models. Wang et al. [31] conducted another RANS computation with a ship model consisting of twin rotating propellers and turning rudders during zig-zag maneuver. Brizzolara et al. [32] conducted a systematic comparison of the hydrodynamic analysis of a propeller using RANS and panel approaches. Bertetta et al. [33] simulated the Contracted Loaded Tip propeller using the potential panel approach and a RANS solver to predict propeller performance. Bertetta et al. [34] also presented a new design method based on a coupling approach between a panel code and an optimization algorithm to design a controllable pitch type propeller at different pitch angles. The new method aimed to reduce the propeller cavitation and correspondingly underwater radiated noise.

The CFD approaches are generally employed to predict propeller performance in cavitating conditions, although the hydrodynamic simulations in this study were conducted in non-cavitating conditions. For instance, Morgut and Nobile [35] performed CFD simulations with two model scale propellers to predict propeller performance in cavitating conditions using three different cavitation models. Gaggero et al. [36] presented a propeller design method, including reliable numerical computations with RANS model to predict the tip and tip leakage vortex cavitation for two ducted and one conventional propeller. Recently, Shora et al. [37] conducted simulations of a marine propeller with different geometrical and physical parameters using CFD methods to predict hydrodynamic performance. ERS typically uses the analysis results of the governing equations that represent the models of propulsion systems. Using the modeling, optimization studies are performed for research studies such as propulsion performance [38]. Piaggio et al. [39] modeled a propeller for an escort tag for a maneuverability model and simulation. However, the aim of this study was different from that defined in these publications. In this study, a maritime propeller was modeled and analyzed to obtain the thrust and torque relationship with different propeller parameters to use the resulting data in developing a new simulation.

### 1.4. Scope of the Study

In the scope of this study, CFD analyses of a marine propeller were conducted using the data from an existing marine ERS, which was developed by Kongsberg Norcontrol AS, located at the Istanbul Technical University Maritime Faculty (ITUMF) campus, and is currently employed in the education and training of marine engineering students and maritime personnel. The development of these types of simulators is crucial for educating new members in the maritime sector. In this respect, the primary aim of this study is to design a more efficient propeller than the existing one to predict the performance parameters and develop a new propulsion system to be employed in developing a new ERS.

The authors of this study designed a new propeller using the trust requirements for a specific ship and obtained the propulsion data using CFD analysis. This study's novelty is to design a more efficient propeller for a newly developed ERS using the CFD approach for a better understanding of the dynamics of the propulsion system and using it to explain the new cadets more professionally.

Within the framework of the above introduction and main objective, this study focuses on a more efficient propeller design than the propeller operating in an existing ERS, simulating the hydrodynamic performance of the propeller, and comparing the CFD simulation results with the simulator's outputs. Furthermore, this study presents the design procedure of a marine propeller using ERS data as inputs. The paper continues with the presentation of an approach that has been used in this study, including the general approach and the process at §2. The propeller design procedure has been presented in §3, including ship resistance computations, propeller initial design, and propeller's parameters. The details and the findings of CFD simulations for the propeller geometry in various operating conditions have been demonstrated in §4. Finally, the study concludes with remarks and discussions in §5, presenting the propulsion data obtained for use in modeling and simulation of the propulsion system in the ERS.

The authors' simulator modeling based on propulsion system analysis is the first publication of its kind, providing a detailed demonstration of how to obtain model data. The presented data and methodology can be used by simulator developers in their developmental studies.

## 2. Methodology

### 2.1. General Approach

A custom propeller was modeled and examined for a large container ship. The analysis considered the maneuvering modes of the engine, which were obtained from the existing ERS, as described in §1. Figure 1 illustrates the conceptual application of the propeller to be employed in a ship propulsion system with the maneuvering modes of the engine. In this study, the maneuvering modes are called the operational modes of the engine with respect to its speed in RPM. Thus, in practice, these modes are called RPM modes. These modes are called the engine's RPM modes in this study. In these modes, the engine has predefined speed values. The RPM modes create boundary conditions in

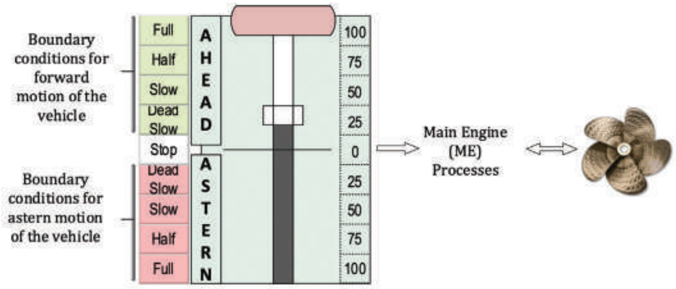


***Figure 1.*** *Conceptual view of propeller analyses with respect to the RPM modes of the main propulsion engine*

terms of the load or resistance that develops with respect to the speed of the propeller. The performance of the designed propeller was analyzed for each of these RPM modes.

This study explains the modeling and development process of a marine propeller. The author's primary interest is to design a new propeller model and simulate its hydrodynamic performance employing CFD approaches and obtain well-structured parametric data for use in simulator development. A simulation platform development effort has been continuing in parallel to this study, which is planned to be published at a later date. The simulator called the ship ERS will be used in the training of marine engineering cadets. In such simulations, all systems of the ship's engines and systems must run interactively and be displayed in real-like gauges and indicators at different ship speeds. In such environments, the aim is not to conduct continuous analysis but to display and change parameters dynamically at a relatively fast rate. Thus, the authors performed analysis for each mode of the engine's RPM modes and established a matrix of the outputs representing the ship's propulsion parameters, to effectively use the results in the operation of the simulator.

The ship dimensions and the general characteristics were selected from the existing simulator employed in this study (Table 1). This simulator was used in the training of marine engineering cadets since 2003 by the ITUMF ERS lecturers. In this study, this simulator is called "Existing Simulator" and the simulator where the output data will be used is called "Future Simulator" for distinguishing from each other.

### 2.2. Process

The first step of this process is to identify the ship and its operational and environmental conditions, as shown in Table 1. Figure 2 illustrates the overall methodology and procedure of modeling and analysis of a propeller obtaining data to use in the simulator application. The process demonstrates the iterative improvement in the propeller design employing the CFD analysis findings and can be listed, in respective order, as follows:

***Table 1.*** *General characteristics of the ship*

| Specifications | Value | Unit |
|---|---|---|
| Type | Container | |
| Cruise speed | 25 | knots |
| Length | 295.00 | m |
| Width (B) | 32.00 | m |
| Draft (T) | 12.60 | m |
| Displacement | 5500/93500 | TEU*/ton |
| Engine power | 48600 | kW |
| Engine speed (@ Navigation full/cruise speed) | 102 | RPM |
| *TEU: Twenty-foot equivalent unit | | |

- Develop specifications (Sec 2.1),
- Compute ship resistance and obtain power-speed data (Sec 3.1),
- Obtain propulsion requirements (Sec 3.2.1),
- Propeller design (Sec 3.2.2),
- Perform CFD analysis (Sec 4),
- Compare performances of new and existing propellers (Sec 5),
- Provide propeller performance data for the new propeller design (Sec 5).

## 3. Propeller Design

### 3.1. Ship Resistance

Before the propeller design process, the total resistance and power requirements of the ship must be computed under various operational conditions and ship speeds. For this purpose, first, the total ship resistance, $R_T$, was computed using various ship speeds, with Maxsurf software and a MATLAB code, for finding the power requirements for the propulsion. Figure 2 demonstrates the force equilibrium of forces due to the ship's speed in a forward direction.

Figure 2 illustrates the changing power requirements due to the losses of the propulsion system, where $P_E$, $P_B$, $P_D$, and $P_T$ represent effective power, engine brake power, propeller-delivered power, and propulsion power, respectively. V

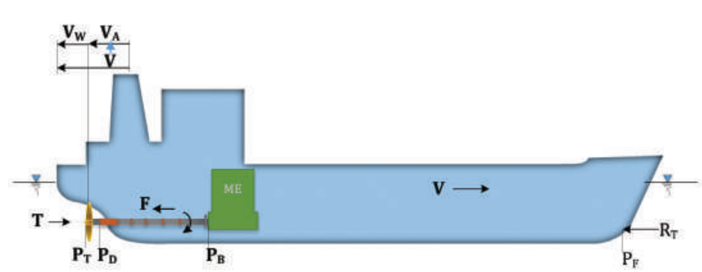


***Figure 2.*** *A conceptual drawing for modeling the ship's power and resistance relations*

represents the ship's speed and VA represents the advanced speed of the propeller. $R_T$ represents the total resistance of the ship.

The ship's resistance can be computed using the following equation:

$$R_T=R_W+R_F+R_{VP} \quad (1)$$

where $R_W$, $R_F$, and $R_{VP}$ represent wave making, friction, and viscous pressure resistances, respectively. Maxsurf HullSpeed module, which uses the Holtrop-Mennen approach, was employed for computing the total resistance and the required propulsion force [40]. Furthermore, a MATLAB code was developed to compute the total resistance of the ship, and the findings were also compared with Maxsurf computations in Figure 3.

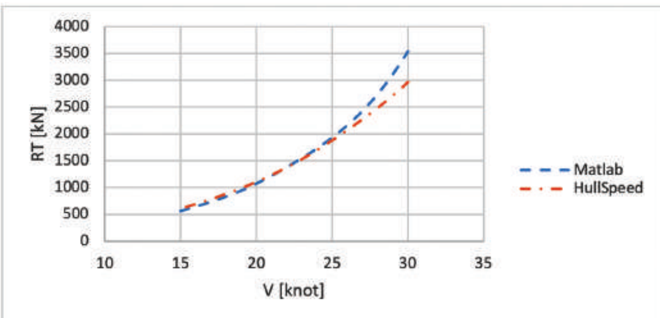


***Figure 3.*** *Ship resistance data obtained using MATLAB Code and Maxsurf*

The total resistance of the ship was computed using various ship speeds within the operational range of the ship: 15-30 knots in both computations. The findings are plotted and illustrated in Figure 3, including the comparison between Hullspeed and MATLAB results. The findings were very close up to 25 knots ship speed; however, there was a noticeable difference above 25 knots. Although the same numerical method [40] was employed for both computations, the deviations between these two approaches can be explained by geometrical effects. While the HullSpeed module employs a three-dimensional (3D) ship model, the MATLAB code uses the main dimensions of the ship to compute the total resistance of the ship, which affects the computation of the total resistance. The discrepancy for higher velocity can be explained as a reason for these different inputs for the computations. The findings demonstrate that the MATLAB code can offer very close results for this case within the operational speed ranges. It was in the authors' special interest that the MATLAB code was developed to validate and employ in the parametric simulator development. Using this code, ship speed, resistance, and power requirements for different ship sizes can be determined without an external code in the simulator program.

The power requirements of the ship were also obtained from the Maxsurf HullSpeed program, including ship speed against power. In this section of the study, the power requirement was around 44000 [kW] for achieving the cruise speed of the ship (25 knots), which is the same power specification that is obtained from the simulator.

## 3.2. Propeller Initial Design

### *3.2.1. Propulsion requirement*

The authors employed the mathematical modeling approach for describing the relationship between the total resistance and propeller thrust due to the lack of the model ship test data. Wake fraction, *w* and thrust deduction, *t* can be computed using the equations as follow [41] :

$$w = 0,5 * C_B - 0,05, \quad (2)$$

$$t = 0,058 + 0,188 * C_B, \quad (3)$$

where $C_B$ represents the block coefficient of the vessel.

Using Equations 2 and 3, wake fraction (*w*) and thrust deduction (*t*) was computed to be 0.198 and 0.151, respectively.

The relationship between the propeller thrust and ship resistance can be computed using the following equation [28]:

$$T_P = \frac{R_T}{n_{propeller} * (1-t)} \quad (4)$$

where $T_p$ represents the propeller thrust and n represents the revolution speed of the propeller. All symbols employed in this study's computations are defined in Table 2 to ease the readability of the manuscript.

For a cruise ship speed of 25 knots, using the ship's resistance at this speed obtained from Figure 3 and inserting n and t into Equation 4, propeller thrust to use in the propeller design, was found as $T_p$= 2238.527 kN. Using the resistance and thrust requirements of the propeller shown in previous sections, the findings were compared to the characteristics of the main diesel engine employed in the existing ERS (Table 3).

The torque limit of the engine can be computed as follows:

$$P_B=2 * \pi * Q * n \quad (5)$$

or

$$Q = \frac{P_B}{2 * \pi * n} \quad (6)$$

where $P_B$, Q, and n represent the engine brake power, torque, and revolution speed of the propeller, respectively. The engine is directly coupled to the propeller without a reduction gear. Using Equation 6, the torque was computed for the power at cruise speed as 4552.26 kNm. Assuming the shaft efficiency of 95%, the torque would be 4324.65

kNm with 46170 kW of the transmitted power to the propeller.

### 3.2.2. Propeller initial design

Although there are several parameters for developing a custom propeller for a ship, the main propellers design parameters such as diameter, pitch ratio, number of blades, expanded area ratio (EAR), skewness, rake, thickness, blade section profile, and material type are considered in this study. The following paragraphs explain the design considerations made for each of these parameters.

**Table 2.** *Nomenclature*

| Symbol | Meaning | Symbol | Meaning |
|---|---|---|---|
| L | Length (m) | $P_T$ | Propulsion Power (kW) |
| B | Breadth (m) | $P_E$ | Effective Power (kW) |
| T | Draught (m) | w | Wake Fraction (-) |
| V | Velocity (m/s) | t | Thrust Deduction (-) |
| $V_A$ | Advanced Velocity (m/s) | $C_B$ | Block Coefficient (-) |
| F | Force (kN) | n | Revolution Rate (rps/rpm) |
| T | Thrust (kN) | n | Propeller Blade Number (-) |
| $T_P$ | Propeller Thrust (kN) | $A_E$ | Expanded Area (m$^2$) |
| Q | Torque (kNm) | $A_o$ | Propeller Disc Area (m$^2$) |
| $R_T$ | Total Resistance (kN) | Z | Propeller Blade Number (-) |
| $R_W$ | Wave Making Resist. (kN) | $P_0$ | Static Pressure (N/m$^2$) |
| $R_F$ | Frictional Resistance (kN) | D | Propeller Diameter (m) |
| $R_{VP}$ | Viscous Press. Resist. (kN) | $P_v$ | Saturation Pressure (N/m$^2$) |
| P | Pitch | x | Dist. between shaft and hull (m) |
| P/D | Pitch to Diameter Ratio (-) | J | Advance Ratio (-) |
| s | Propeller Slip | $K_T$ | Thrust Coefficient (-) |
| $P_B$ | Break Power (kW) | $K_Q$ | Torque Coefficient (-) |
| $P_D$ | Delivered Power (kW) | ♒$_0$ | Open Water Propeller Eff. (-) |

**Table 3.** *Propulsion engine (main diesel engine), Sulzer RTA 84C, characteristics*

| Specifications | Value | Unit |
|---|---|---|
| Cylinder diameter (bore) | 84 | [cm] |
| Piston stroke | 240 | [cm] |
| Number of cylinders | 12 | [-] |
| MCR | 48600 | [kW] |
| Engine speed | 102 | [rpm] |
| Fuel consumption | 171 | [g/kWh] |

### 3.2.3. Propeller diameter (D) and number of blades (N)

The propeller thrust must be maximized to have the maximum propulsion power, which is converted from the engine brake power most efficiently by the propeller. Thus, the propeller diameter can be selected to be close to the maximum [28], considering the minimum clearance between the tip of the propeller and the hull structure.

Using the guidance of the [42] publication, the clearance between the hull structure and propeller tip and maximum diameter was computed as follows:

$$\text{Propeller clearance} = \frac{25 * x}{75} \tag{7}$$

where x represents the distance between the shaft and hull structure above the propeller's centerline, which is around 5.9 m, using the 3D ship model, which was modeled in this study. Thus, the required clearance and the maximum propeller diameters were computed as 1.9 m and 7.8 m, respectively. Considering the operational needs explained in the above paragraphs and the maximum propeller clearance obtained using Equation 7, the diameter, D, was selected as 7.8 m.

The propeller for this type of ship is assumed to have number of blades between 2 and 6. The propeller efficiency could be higher as the number of blades selected is minimum, while the mechanical loads on each blade would be higher. Thus, propellers for high-pressure operation and high propulsion load requirements are usually selected to have more than four blades. Since the ship propulsion loads would be very high for this ship type (Table 1), the number of blades, N, selected for this ship was 5. In optimization studies, the recommendation is to repeat the modeling and analysis of various numbers of blades to determine the most suitable number of blades for a specific application.

### 3.2.4. EAR and pitch ratio (P/D)

The ratio of EAR to blade area, of 0.55 is commonly accepted to be ideal. The pitch (P) is computed using the propeller slip (s) in the water [28], as follows:

$$P = \frac{V}{(1 - s) * n} \tag{8}$$

With ship speed of 25 knots and a propeller revolution speed of 102 rpm, as well as a slip rate of the propeller of 0.15, using Equation 8, P was computed to be 8.9 m, which yields a ratio of P/D of 1.14.

For computing EAR, Keller cavitation criterion [43], which is represented by Equation 9, were used as the initial method for identifying the cavitation.

$$\frac{A_E}{A_0} = \frac{(1{,}3+0{,}3*Z)*T_P}{(P_0-P_V)*D^2} + k \quad (9)$$

where,

$A_E$ represents the expanded area

$A_0$ represents the propeller disc area

Z represents the number of blades

$T_P$ represents the propeller thrust [N]

$P_0$ represents the static pressure at the propeller centerline [N/m$^2$]

D represents the propeller diameter [m]

$P_V$ represents the saturation (vapor) pressure (~1700 [N/m$^2$])

and k is a coefficient determined by the ship type, speed, and the number of propellers. For slow-speed cargo ships, k is used as 0.1 [43].

The thrust power, $T_p$, was entered from the result of Equation (4) as 2238.527 kN. Using $P_0 = P_{atm} + \rho g h_s$, $P_0$, the pressure on the centerline of the propeller was computed as 174326.115 [Pa]. The dimensionless EAR parameter value in this study was considered to be 0.7 because this number should be smaller than that found using Keller's formula.

### *3.2.5. Propeller geometry*

The propeller initial model was established employing the Wageningen propeller series [44]. In later sections of this study, the authors present the changes made to this initial model after evaluating the findings obtained in the CFD analysis. The blade geometry was developed in a propeller design application considering an EAR value of 0.7 and the pitch values are obtained using the lifting line approach. Table 4 displays the design parameters and Figure 4 illustrates the 3-dimensional initial propeller and two dimensional projection of the blade model developed and used in the analysis.

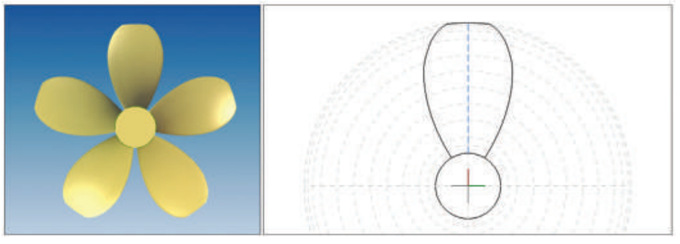

***Figure 4.*** *Initial propeller design and 2-D projection of the blade*

***Table 4.*** *Initial propeller design parameters*

| Parameter | Value | Unit |
|---|---|---|
| Number of blades | 5 | [-] |
| Diameter | 7.8 | [m] |
| Propeller shaft diameter | 1.560 | [m] |
| Extended area ratio | 0.702 | [-] |
| Average pitch | 9.013 | [m] |
| Average pitch ratio | 1.156 | [-] |

Blade section profiles were selected using a = 0.8 Mean Line (mod) and National Advisory Committee for Aeronautics 66 (mod) used for the thickness profile.

The blade thicknesses associated with various blade diameters were computed using the rules and guides provided by the Turkish Lloyd (TL) Class organization [45]. Using TL guides, the propeller material was selected is a cupper-manganese-aluminum alloy, commonly known as CU4 type, with a tensile strength of 630 N/mm$^2$. The thickness criteria using the TL guides offer the following information for different radii: For 0.25xR, t ≥ 367.31, for 0.35xR, t ≥ 306.20, and for 0.6xR, t ≥ 207.03.

## 4. CFD Analysis of the Propeller

### 4.1. Validation and Verification Studies with Standard Test Propellers

CFD simulations were performed on the new propeller design for a container ship to obtain data for use in an ERS development study. However, before this, the authors analyzed two standard test propellers, Potsdam Propeller Test Case (PPTC) Validation Propeller (VP) 1304 and DTMB 4119 using the RANS method with ANSYS Fluent to validate the CFD environment (Figure 5). The findings of the analyses of the standard propellers were compared with published studies for justification. This subsection briefly summarizes this part of the verification analysis using CFD, and Sections 4.2 through 4.6 provide details of the CFD analysis conducted for the newly designed propeller.

Several researchers [30,32,46,47] have tested and simulated these standard test propellers using experimental fluid dynamics (EFD) approaches. The findings have also been presented in the open literature for validation and verification purposes. In this study, open-water propeller performance findings that have been measured and computed with experiments in the past were used to compare with the CFD simulation findings.

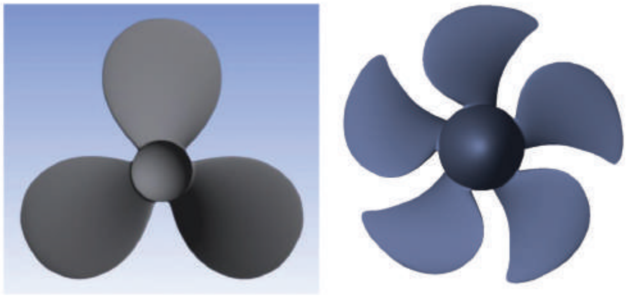

***Figure 5.*** *Validation studies with standard test propellers (left: DTMB 4119, right: PPTC VP 1304)*

For the validation studies, the standard test propellers were simulated with only one blade configuration to reduce the generated mesh and solution time. The moving reference frame method was used to describe the rotation of the flow domain around the propeller blade. The RANS k-ω model was preferred for modeling turbulence in the open-water calculations. Suitable meshes were generated for each propeller case, as illustrated in Figure 6.

The CFD findings for the DTMB 4119 and PPTC VP 1304 propellers were compared with the experiments published in the open literature [30] and [46], respectively, in terms of propeller performance coefficients ($K_T$, $10K_Q$, and $n_0$).

Table 5 displays the comparisons of the propeller performance coefficient between the CFD and EFD results for the DTMB 4119 standard test propeller. The CFD findings showed a deviation of 3% from the experiments. The comparison revealed good agreement not only for propeller performance coefficients but also for the velocity distribution behind the propeller and pressure distribution on propeller surfaces.

Table 5 displays the comparison of the propeller performance coefficient between CFD and EFD results for the PPTC VP 1304 standard test propeller. The CFD findings demonstrated good agreement with the experiments, with a deviation of less than 3%, similar to the findings for the DTMB 4119 propeller CFD findings.

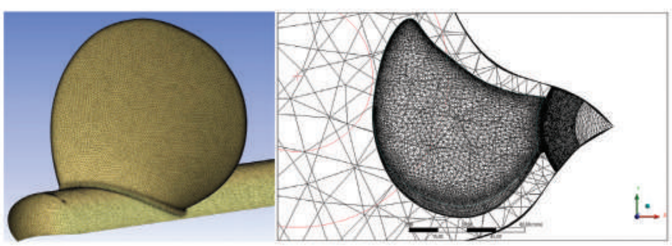

***Figure 6.*** *Generated mesh for one blade (Left: DTMB 4119, Right: PPTC VP 1304)*

*DTMB: David Taylor Model Test Basin, PPTC: Potsdam Propeller Test Case, VP: Validation Propeller*

These validation studies conducted on DTMB 4119 and PPTC VP 1304 standard test propellers confirm that the CFD approach with one-blade analysis, generated mesh, and turbulence model produces highly accurate results for predicting open-water propeller performance. The authors have previously published more detailed results of these validation and verification studies for both propellers [46].

After the validation studies for two different standard test propellers, the same CFD simulation approach was used to analyze the new propeller design for a container ship, which will be employed to develop a new ERS. The analysis approach employed for the new propeller design is presented in detail in the following sections.

### 4.2. Analysis with Computational Fluid Dynamics

The CFD analysis was iteratively conducted using ANSYS Fluent. The propeller performance and efficiency were estimated for each engine RPM modes. Input parameters for CFD simulations were defined for each gas lever position based on simulator outputs. The inputs such as the propeller revolution speed and the expected ship velocity were specified from the ERS for use in CFD computations. The CFD findings, which are thrust and torque values were compared with the existing simulator data. The CFD analyses were simulated for each engine RPM Mode (Figure 1) and presented in Table 6.

### 4.3. CFD Model, Input Data, and Setup

The flow domain was prepared around propeller geometry employing the Design Modeler module of ANSYS. To compute the propeller performance, only one blade was simulated, which reduced the number of mesh and computation time required for the analysis. The flow domain was modeled around the propeller geometry as a

***Table 5.*** *DTMB 4119 Propeller performance coefficient comparisons between CFD and EFD*

| | J [-] | $V_A$ [m/s] | n [1/s] | $K_T$ [-] | $10K_Q$ [-] | $n_0$ [-] |
|---|---|---|---|---|---|---|
| CFD results | 0.833 | 4.5701 | 18 | 0.1442 | 0.273 | 70% |
| EFD results | 0.833 | 4.5701 | 18 | 0.1460 | 0.28 | 69% |
| Deviation (CFD-EFD) | - | - | - | -2% | 1% | -3% |
| CFD: Computational fluid dynamics, EFD: Experimental fluid dynamics | | | | | | |

***Table 6.*** *PPTC VP 1304 Propeller performance coefficient comparisons between CFD and EFD*

| | J [-] | VA [m/s] | n [1/s] | KT [-] | $10K_Q$ [-] | $n_0$ [-] |
|---|---|---|---|---|---|---|
| CFD results | 0.6 | 2.25 | 15 | 0.6159 | 1.4098 | 41% |
| EFD results | 0.6 | 2.25 | 15 | 0.6288 | 1.3964 | 43% |
| Deviation (CFD-EFD) | - | - | - | -2 | 1 | -3 |
| CFD: Computational fluid dynamics, EFD: Experimental fluid dynamics, PPTC: Potsdam Propeller Test Case, VP: Validation Propeller | | | | | | |

rotating domain using the MRF technique to describe the rotational motion. A suitable mesh structure was generated using tetrahedral elements in the flow domain with the ANSYS Meshing module. To generate the mesh, the number of elements, skewness, orthogonal quality, and aspect ratio, were 2251466, 0.89, 0.112, and 41.644, respectively.

### 4.4. Boundary Conditions

Boundary conditions were set for each of the RPM modes for analysis (eight different analysis modes) associated with the engine's maneuvering modes, in the ahead and astern directions, as illustrated in Table 7. The different boundary conditions were set for the inlet patch position due to the direction of flow (ahead and astern) and have been described in detail in the following sections. To model turbulence, the RANS k-ω SST turbulent model was employed for predicting propeller performance. The density of seawater was set to 1025 kg/m$^3$ for the fluid type for all analyses.

#### *4.4.1. Boundary conditions for the analyses in the ahead RPM modes*

During the propeller operation behind the ship, the forward surface of the propeller blade (suction side) facing the upcoming flow was considered the inlet boundary condition, and the back surface (pressure side) was considered the outlet boundary condition for the CFD analyses in the ahead RPM modes. The water flow velocity associated with ship speeds of 9.16, 14.68, 21.01, and 25 knots, was determined in meter-per-second. The outlet boundary condition was defined as a pressure outlet condition at 0 Pa. The propeller's blade, hub, and shaft surfaces were described as "no slip wall" boundary conditions. The surface on the outward direction from the flow domain was selected as symmetry. The interface for 1/5 flow volumes was defined as the periodic boundary conditions and described as periodically sequenced in ANSYS Fluent. Figure 7 shows the summary of the boundary conditions depicted on the model for analysis.

#### *4.4.2. Boundary conditions for the analyses in the astern RPM modes*

For the analyses in the astern RPM modes, the forward surface of the propeller blade (suction) was considered the outlet side, and the back surface (pressure) was considered the inlet side of the propeller, similar to the analyses in the ahead RPM modes. The boundary conditions used in the analyses of the ahead RPM modes were kept the same for the propeller analyses of the astern RPM modes, except that the positions of the inlet and outlet were changed. A pressure outlet condition of 0 Pa was set at the outlet side of the propeller. The required inflow velocities were also changed to 6.98, 11.68, 14.28, and 19.57 knots of ship speed occurring from ship's backward directional motion.

***Table 7.*** *Gas lever position (RPM modes)*

| Parameters | Full ahead | Half ahead | Slow ahead | D. slow ahead | D. slow astern | Slow astern | Half astern | Full astern |
|---|---|---|---|---|---|---|---|---|
| Ship speed [knots] | 25.05 | 20.01 | 14.68 | 9.16 | -6.98 | -11.68 | -14.28 | -19.57 |
| Propeller speed [rpm] | 102 | 80.02 | 58.01 | 36 | -36.03 | -55.04 | -73.42 | -92.11 |
| Propeller power [mW] | 42.89 | 19.72 | 7.25 | 1.7 | 2.27 | 16.28 | 19.1 | 30.58 |
| Propeller thrust [kN] | 2490.47 | 1404.65 | 691.75 | 257.03 | -418.8 | -655.85 | -1721.1 | -1918.1 |

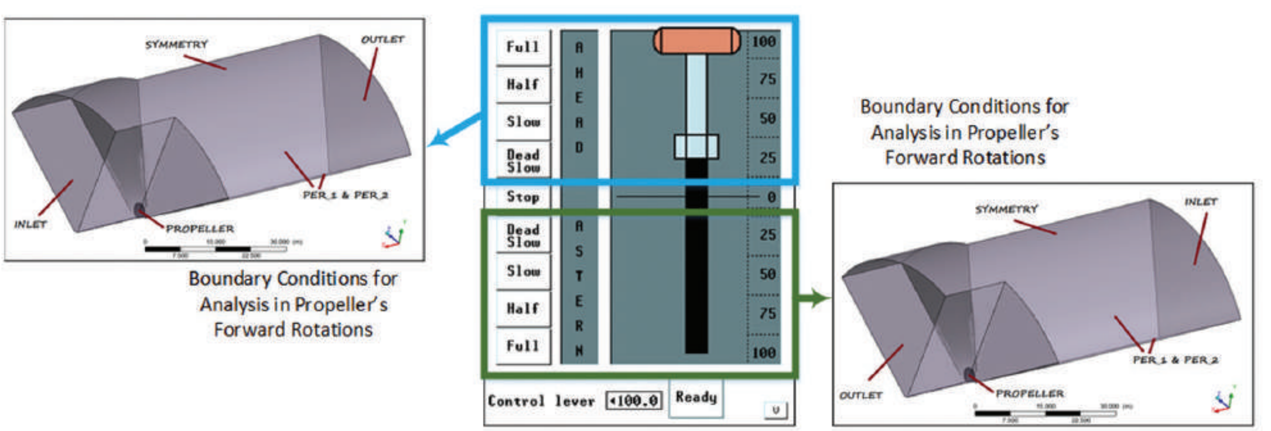


***Figure 7.*** *Boundary conditions shown on the propeller model for the analysis in the ahead and astern RPM modes*

*RPM: Revolutions per minute*

## 5. Results and Discussion

Analyses for eight RPM modes associated with the engine's maneuvering modes in ahead and astern directions were conducted to compute the hydrodynamic performance of the propeller (Table 7 and Figure 7). Figure 8 illustrates the flow velocity distributions behind the propeller blades and shows the pressure distributions on the propeller surfaces. These distributions demonstrated in Figure 8 represent the analysis for one of the ahead RPM modes, provided as an example.

Table 8 displays the comparisons of the propeller performance coefficient for existing and new design propellers for ahead RPM modes. The data demonstrate that the open-water propeller efficiency increased by about 5%-9% with the new propeller.

When compared with the existing simulator data, the new propeller demonstrated a little more thrust in the ahead RPM modes (Figure 9a) and lower power requirements at the same modes (Figure 9b).

Table 9 shows the input parameters, such as ship speed ($V_s$), propeller speed ($V_a$), advance velocity ratio ($j$), propeller's rotational speed ($n$), as well the outputs, including propeller thrust ($V_s$), torque ($Q$), and computed performance parameters, thrust coefficient ($K_t$), torque coefficient ($10K_Q$) and open-water propeller efficiency ($n_0$). The data from Table 9 and Figure 10 were used to model and simulate the propulsion system. The novelty of this study is the development of a propulsion modeling process for a new ERS application. Figure 10 illustrates a screen capture of the Graphical User Interface (GUI) for the Propulsion System panel employed in the new simulator. Parametric modeling enabled the simulator to alter propulsion parameters, including meteorological ones that affect propulsion

***Table 8.*** *Propeller efficiency comparison between existing and new design*

| Propeller | Performance coefficients | Ahead 100 | Ahead 75 | Ahead 50 | Ahead 25 |
|---|---|---|---|---|---|
| New design | $K_T$ | 0.233 | 0.225 | 0.220 | 0.217 |
| | $10K_Q$ | 0.445 | 0.434 | 0.428 | 0.425 |
| | $n_0$ | 65% | 65% | 66% | 66% |
| Existing design | $K_T$ | 0.227 | 0.208 | 0.195 | 0.188 |
| | $10K_Q$ | 0.469 | 0.447 | 0.431 | 0.423 |
| | $n_0$ | 60% | 59% | 58% | 57% |

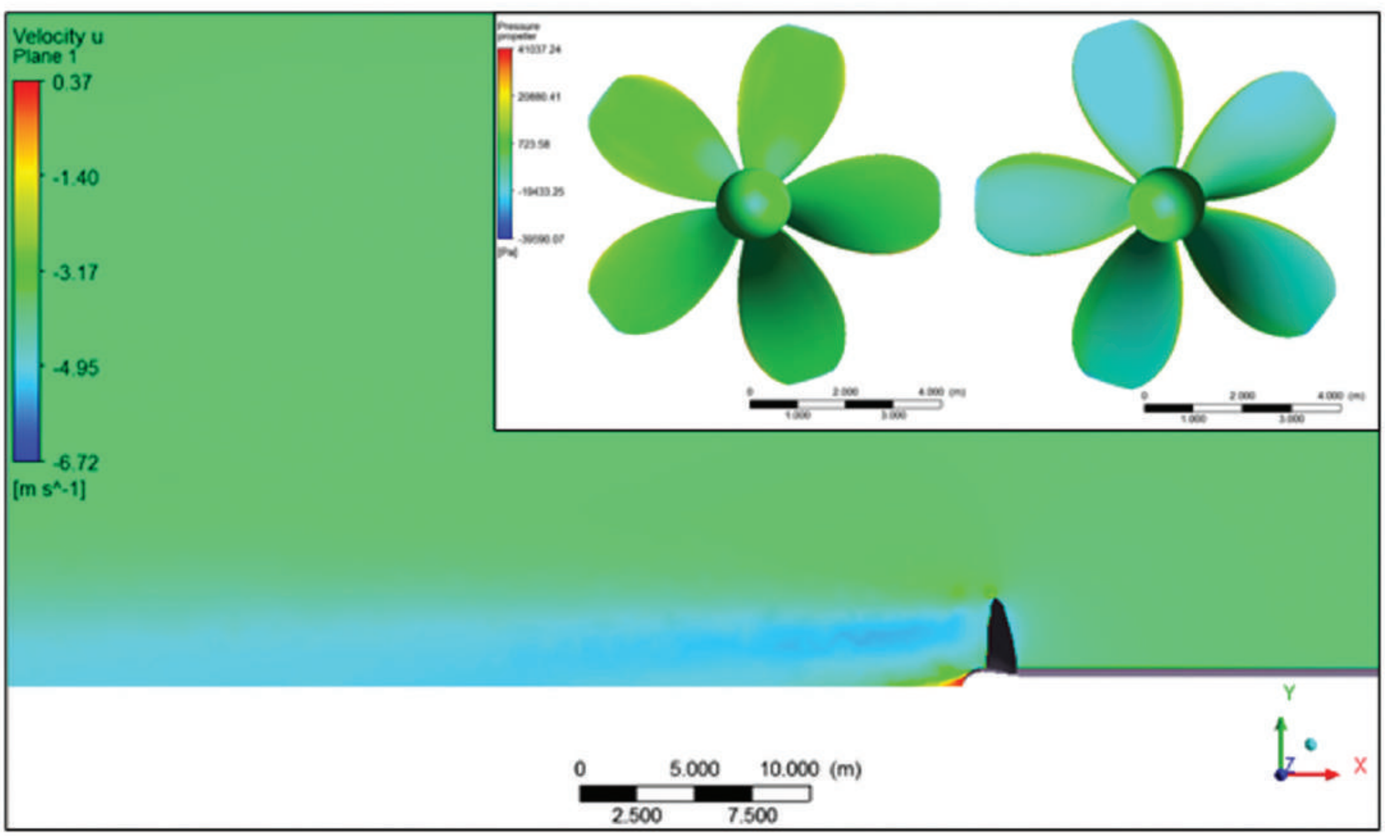


***Figure 8.*** *Velocity distribution behind the propeller and pressure distributions on the propeller surfaces for ahead RPM modes of analyses (left: pressure side, right; suction side)*

*RPM: Revolutions per minute*

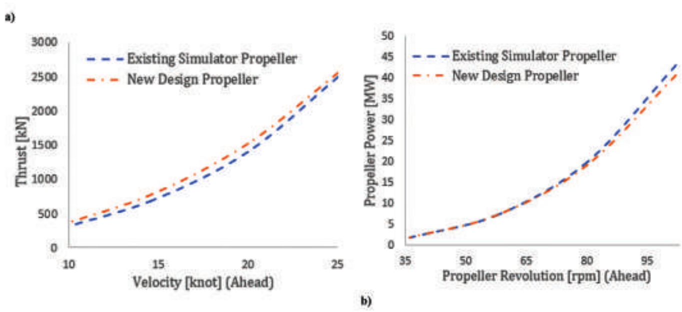


***Figure 9.*** *Comparison of ship speed and propulsion a) force, and b) power in ahead RPM modes*

*RPM: Revolutions per minute*

performance. The parametric simulation programming also facilitated the implementation of student exercises, such as propeller slip rate and similar ones described in IMO Model Course 2.07 [8].

## 6. Conclusion

This study introduces a new propeller design and CFD analysis to obtain propulsion data, which be used to develop a training simulator. To this end, the study has successfully achieved the following.

• Ship resistance computations were conducted using Maxsurf Hullspeed software and MATLAB code with the

***Table 9.*** *CFD analysis results*

| | RPM modes | Ship vel. ($V_S$) | Adv. vel. ($V_A$) | Adv. ratio (J) | Rev. (n) | Thrust (T) | Torque (Q) | Thrust coeff. ($K_T$) | Torque coeff. $10K_Q$ | Open water eff. ($n_0$) | Delivered power ($P_D$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | [knot] | [m/s] | [-] | [rpm] | [kN] | [kNm] | [-] | [-] | [-] | [MW] |
| Inlet | Ahead 100 | 25.05 | 10.33 | 0.779 | 102 | 2554.50 | 3806.75 | 0.233 | 0.445 | 65% | 40.65 |
| | Ahead 75 | 20.01 | 8.26 | 0.793 | 80 | 1519.50 | 2287.65 | 0.225 | 0.434 | 65% | 19.16 |
| | Ahead 50 | 14.68 | 6.06 | 0.803 | 58 | 780.77 | 1184.96 | 0.220 | 0.428 | 66% | 7.19 |
| | Ahead 25 | 9.16 | 3.78 | 0.807 | 36 | 297.04 | 453.78 | 0.217 | 0.425 | 66% | 1.71 |
| Outlet | Astern 25 | 6.98 | 2.88 | 0.614 | 36 | 294.98 | 476.74 | 0.215 | 0.446 | 47% | 1.79 |
| | Astern 50 | 11.68 | 4.82 | 0.673 | 55 | 579.26 | 963.41 | 0.181 | 0.386 | 50% | 5.55 |
| | Astern 75 | 14.28 | 5.89 | 0.617 | 73 | 1216.81 | 1958.08 | 0.214 | 0.441 | 48% | 15.05 |
| | Astern 100 | 19.57 | 8.07 | 0.674 | 92 | 1616.36 | 2678.8 | 0.180 | 0.384 | 51% | 25.83 |

CFD: Computational fluid dynamics, RPM: Revolutions per minute

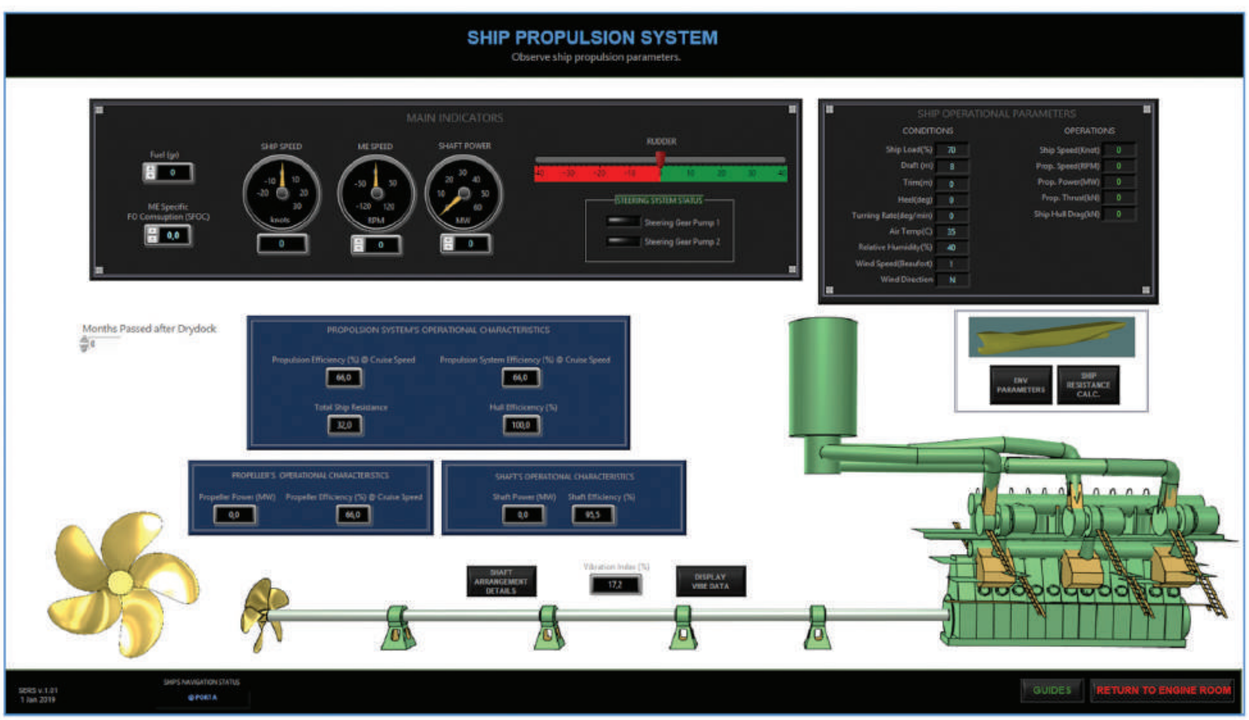


***Figure 10.*** *Ship Propulsion System GUI Window captured from the new simulator, which is developed using the data from this study*

Holtrop-Mennen method to determine the hull resistance and thrust requirements of the propeller.

• A new propeller was designed based on the propulsion requirements of the simulated ship.

• Validation investigations were conducted using two standard test propellers (DTMB 4119 and PPTC VP 1304) before performing CFD computations for a new propeller design and validating the CFD approach employed in this study. The CFD findings were also compared with those in the literature, and a good agreement was achieved.

• The new propeller was simulated using CFD approaches with commercial CFD software, ANSYS Fluent, at different RPM modes of the main propulsion engine.

• The CFD findings of the new design propeller were compared with the findings of the existing propeller that were obtained from the ERS. The comparison demonstrated a good agreement in terms of propeller performance coefficients, particularly for open-water propeller efficiency. The new design offered more thrust with less power requirement than the existing propeller.

• Propulsion data, including the propulsion performance, torque, and efficiency, were constructed.

The model was developed by employing the existing simulator as a test system to obtain the ship propulsion parameters associated with the engine's speed and load characteristics. The data obtained from the existing simulator is representative of a container-type ship with a fixed-pitch propeller. Another investigation study for this case, including uncertainty studies, is also planned as a future study.

The propeller design, developed equations, and performance analysis findings obtained in this study were crucial not only for providing data for modeling but also for enhancing understanding of the propulsion system modeling, developing a new simulator, and educating new cadets in the marine community. Additional research may further improve this study, as follows:

• A non-dimensional form of the equations could be developed and examined so that the resulting matrix could be directly applied to other types of ships with a fixed-pitch propeller.

• Simulator design and development could be described in a future study, including a discussion of the software architectures and education outcomes.

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**Peer-review:** Externally and internally peer-reviewed.

## Authorship Contributions

Concept design: Data Collection or Processing: Analysis or Interpretation: Literature Review: Writing, Reviewing and Editing: All authors have contributed equally.

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# Sustainable Compensation Strategies for Ship Owners Liability for Occupational Injury and Death Costs Affecting Seafarers in Nigeria

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## Abstract

The study developed strategies for reserving funds for adequate and sustainable compensation of injury and death costs affecting seafarers in Nigeria. This study aims at quantifying the output losses resulting from occupational injury and death suffered by seafarers, as well as calculating the coefficients of the average rate of change of injury and death costs between 2006 and 2019 in Nigeria. The study utilized time series data from secondary sources. The Gross Output Method was used to assess the costs of occupational injury and death affecting seafarers for which ship owners are liable to provide compensation. The rate of change analysis was employed to estimate the coefficients of the average rate of change of injury and death costs. The results provided the basis for developing empirical relationships to ensure the reservation of sufficient funds by underwriters to sustainably compensate injury and death costs affecting seafarers in the Nigerian maritime industry.

**Keywords:** Compensation, Strategies, Injury cost, Death costs, Seafarers, Ship owners, Liability

## 1. Introduction

Maritime is an extremely demanding and risky industry. Illnesses, injuries, and fatalities occurring while working at sea are significantly higher compared to other occupational groups [1,2]. The Maritime Labor Liability policy provides insurance coverage and/or protection against illnesses, injuries, and fatalities experienced by maritime workers (seafarers) during their employment. Ship owners' liability with regards to compensating maritime workers/seafarers in the event of occupational-related illnesses, injuries, or death is derived from the provisions of the Maritime Labour Convention (MLC), 2006, by the International Labour Organization (ILO) [3]. Regulation 4.2 of the MLC 2006 establishes that the ship owners are responsible for securing sufficient measures to guarantee that seafarers/ maritime workers are safeguarded from the financial repercussions of occupational-related illnesses, injuries, or death, occurring in association with their employment [3]. The stipulations of the MLC (2006) apply to seafarers working on a vessel of a country that has ratified the MLC 2006, or where a vessel trades in a country that has ratified the MLC 2006. It applies to all vessels engaged in commercial activities at sea, without extension to ships engaged in trade in and navigating the inland waterways. Additionally, it may not apply to vessels involved in fishing activities, warships, and other categories of coastal vessels that local regulations and laws specify. Regulation 4.2 section (b) explicitly states that ship owners ought to provide financial security to guarantee compensation in the instance of the death or long-term disability of seafarers due to an occupational injury, illness, or hazard, as established in national laws, the seafarers' employment agreement or collective agreement; while Regulation 4.2.1, paragraph 1(b), specifies that the ship owner should be subscribed to an insurance scheme or fund to be able to meet maritime labor liability risks and ensure adequate compensation of seafarers in cases of death and injury arising from work-related accident [3].

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The convention stipulates the conditions under which a ship owner may be exempt from liability. Nigeria ratified the MLC 2006 on June 18th, 2013, when the government deposited the instrument of ratification with the International Labour Office [2,3]. According to the ILO, Nigeria is the 37th ILO Member State and the fifth state from the African region, after Benin, Liberia, Morocco, and Togo, to have ratified the MLC 2006 in 2013.

However, the Nigerian maritime industry is deeply concerned about the seriousness and approaches to enforcing the provisions of the MLC, 2006. Several reports of seafarer abandonment by ship owners (employers) following work-related injuries and deaths have been received. To comply with the MLC, 2006, ship owners purchase marine insurance policies to provide adequate funds for compensating work-related illnesses, injuries, and deaths of seafarers. Marine underwriting firms are required to provide compensation for maritime labor liability risks when they occur. The International Monetary Fund (IMF) [4] has reported faults in the Nigerian insurance sector, identifying the lack of financial solvency and capacity to adequately compensate insured risks. The behavior of ship owners abandoning local seafarers without compensation in the event of occupational injury, illness, and death is viewed as a consequence of the financial insolvency and incapacity of marine underwriters and insurers to provide adequate compensation in the event of an insured risk [4-6].

Studies referenced in [7,8] have identified the insolvency problem faced by underwriters in the Nigerian marine insurance industry. The issue stems from the arbitrary allocation of 25% to 45% of generated premium income to the technical reserve fund, as stipulated in the Nigeria Insurance Act [8,9]. This has resulted in many insurers becoming insolvent when compensating claims, particularly those related to maritime labor liability in Nigeria. Furthermore, the Nigerian marine insurance subsector is currently underdeveloped in terms of the maritime labor/employee liability insurance trade, as stated in [9-12]. Financial insolvency is another challenge that has limited underwriters' capacity to indemnify claims, thereby influencing ship owners' decisions to evade, limit, and/or deny liability for injury, illness, and death costs affecting seafarers. Ship owners outsource seafarers' employment to third-party contractors and crewing companies that differ from their own. The MLC, 2006, exempts ship owners from illness, injury, and death liabilities for employees who are not direct employees of the ship owners, such as contract staff [13]. One of the challenges faced by marine underwriters in addressing these issues is the problem of the database, which has made it impossible to develop empirically based knowledge and models of relationships that can guide underwriters in providing an adequate volume of funds as a technical reserve for unexpired risks. Overcoming the challenges of financial insolvency requires addressing this problem and developing better risk assessment and management models.

To formulate a maritime labor liability insurance regulation that can address the challenges of financial insolvency in compensating insured risks for both public and corporate (private/individual firm) levels, a historical overview of the burden of occupational injury and death affecting seafarers in Nigeria must be examined to determine the compensation needed. This analysis will provide an understanding of the trend of occupational injury and death burden affecting seafarers, along with the associated costs that marine insurers must adequately and sustainably provide compensation for annually. The second step requires evaluating the average rate of change of the cost of occupational injury and death associated with seafarers. Since underwriters are responsible for adequately compensating the economic cost, the amount of annual loss/cost will influence the funds to be reserved for risk compensation, which in turn affects the premium that underwriters will be willing to charge for providing coverage to affected employees/seafarers and their families [14-17].

The average rate of change for both the cost of injury burden and death will serve as the basis for establishing an empirical model that enables insurers to reserve adequate funds to address financial insolvency challenges for sustainable compensation of insured maritime labor liability costs in Nigeria. It is essential to note that despite the loopholes and problems identified in the current marine underwriting practices and the provision of compensation funds for insured employee liability costs that ship owners are responsible for in Nigeria, such as the insolvency of underwriters in maintaining adequate compensation funds for timely and sufficient compensation of injury and death costs affecting seafarers, and the lack of a basis to ensure adequate protection and compensation of maritime labor liability risks in line with the provisions of the ILO's MLC, the available empirical literature has only focused on identifying the inadequacies of the prevailing compensation regime in the Nigerian marine insurance sector. There has been no attempt to provide empirical knowledge-based approaches to overcome these inadequacies. This study aims to achieve the following objectives as a contribution to knowledge and in response to the identified research questions.

## 2. Aim and Objectives of the Study

This study aims to establish empirical relationships that ensure the adequate reserve of funds by marine underwriters for sustainable compensation of injury and death costs affecting seafarers in Nigeria, for which ship owners are liable.

The study has specific objectives, which are as follows:

(i) To assess the economic costs of occupational injuries in the Nigerian maritime industry affecting seafarers, for which ship owners bear responsibility.

(ii) To estimate the cost of work-related deaths in the Nigerian maritime industry affecting seafarers.

(iii) To determine the coefficient of the average rate of change of the economic cost of occupational injuries in the Nigerian maritime industry affecting seafarers.

(iv) To estimate the coefficient of the average rate of change of the cost of work-related deaths affecting seafarers in the Nigerian maritime industry.

(v) To develop empirical conditions of relationships for the reservation of funds for adequate and sustainable compensation of maritime labor liability risks in Nigeria.

### 2.1. Research Questions

Per the objectives of the study, the following research questions have been identified:

(i) What is the economic cost quantum of occupational injuries that affect seafarers in the Nigerian maritime industry, for which ship owners are liable?

(ii) What is the estimated cost of work-related fatalities that affect seafarers in the Nigerian maritime industry?

(iii) What is the coefficient of the average rate of change of the economic cost of occupational injuries that affect seafarers in the Nigerian maritime industry?

(iv) What is the coefficient of the average rate of change of the cost of work-related fatalities that affect seafarers in the Nigerian maritime industry?

(v) What empirical conditions can ensure the reservation of adequate funds for the sustainable compensation of maritime labor liability costs in Nigeria?

## 3. Literature Review

The dangers associated with ship-based accidents are complex and multifaceted. In addition to the risk of loss of human capital due to fatalities and injuries, many seafarers who have experienced major ship-based accidents suffer significant psychological trauma that may prevent them from returning to sea [18-21]. The death, injury, and traumatic experiences associated with occupational accidents in the maritime sector have led to symptoms closely related to post-traumatic stress disorder (PTSD) among affected seafarers. Although existing labor laws in Nigeria do not provide for compensation for PTSD, the ILO [3]. MLC explicitly states that it is the ship owner's responsibility to compensate seafarers for losses resulting from occupational illnesses, injuries, and deaths [22-25].

The MLC, 2006 provides that the ship owner should use available instruments, such as insurance protection and Protection and Indemnity (P&I) cover, to secure adequate compensation for affected seafarers. However, it is uncertain to what extent this provision of the MLC 2006 can be employed to secure compensation for seafarers who have suffered from trauma-related disorders, as ship owners in Nigeria tend to disregard compensation for trauma while also evading compensation for physical injuries, illness, and death, which were expressly identified in the MLC, 2006 as falling under the ship owner's liability. In some cases, they tend to focus only on compensation for physical injuries and work-related deaths, and their capacity to fulfill the indemnification of injury and death costs, which are liabilities placed on them by reference [3], seems inadequate, resulting in their evasion and limitation of liability for injury and death costs affecting maritime workers [16,26].

It is important to note that marine accidents resulting in occupational injuries and deaths, in addition to causing loss of crucial workforce and human resources in the marine industry, negatively impact output performance and productivity of the industrial subsector [27-31]. This underscores the need for adequate and sustainable methods of compensating such losses to guarantee sustainable maritime operations. Furthermore, to overcome the problem of financial insolvency faced by marine underwriters, affecting their capacity to provide timely, adequate, and sustainable compensation for insured employee liability risks, there is a need for the development of empirically based knowledge to ensure adequate funds are reserved for that purpose. Achieving this will require a historical estimation of injury and death cost burdens associated with seafarers' exposure to occupational accidents and hazards over the years.

Reference [32] estimated the economic cost of traffic accidents in Nigeria using the Human Capital Model-Gross Output Model (GOM) to determine the wastages and loss in output and productivity of the road transport subsector due to injury and death of personnel. Extending the model to the maritime subsector, one can estimate the output losses associated with occupational injury and death affecting maritime workers [33,34]. Human resources constitute a major component of the maritime industry capital and the productivity and output of the industry depend on the capital resources employed. Therefore, losses, illness, and incapacitation of human capital cannot optimally contribute to output and performance, leading to a decline in productivity and output and making it impossible to guarantee sustainable maritime operations in the long run. Figure 1 below compares the number of deaths of seafarers in the global and Nigerian maritime industries due to work-related accidents.

The figure above illustrates the loss of life globally and in Nigeria due to marine accidents, resulting in a decline in workforce capacity and subsector performance. The study shows an increasing trend in seafarer deaths in Nigeria while global loss of life is decreasing. This trend is likely due to poor compliance with standard safety rules and regulations in the Nigerian maritime industry. The economic losses suffered by the nation, the marine industry, individual seafarers, transoceanic maritime transport, and domestic industry are significant [1,2,35]. Ship owners and companies are responsible for adequately compensating for this economic loss through marine insurance and/or P&I clubs.

The offshore industry safety report by the Department of Petroleum Resources (DPR) [36] highlights the losses incurred in human capital output due to crew injury and death, which have not been adequately compensated for over the years. The report indicates that between 2015 and 2016, an average of 47 maritime/offshore workers died from work-related accidents, while an average of 88 maritime workers suffered serious injuries. Current marine underwriters' practices in Nigeria do not prioritize protecting seafarers from output losses caused by occupational injury and death, which is provided for in the ILO's 2006 MLC. Local seafarers are left to seek personal life insurance protection for occupational injuries and death, which is the ship owners' and operators' liability under the ILO. The local marine underwriting sector can prioritize this need by developing a marine accident human capital cost database for future projections of the economic resources needed to ensure adequate protection and compensation.

The IMF [4] conducted a study on insurers' solvency in

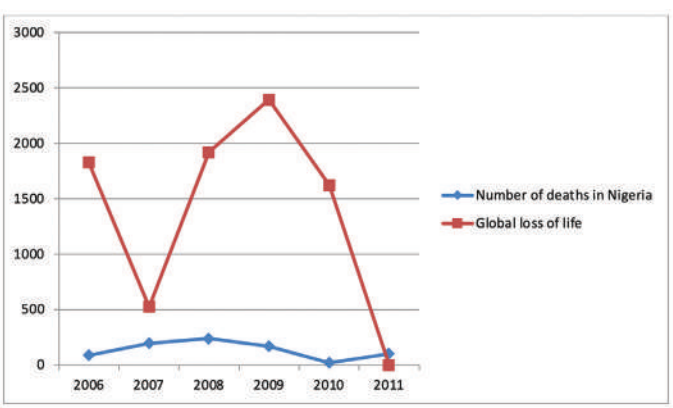


***Figure 1.*** *Trend of marine accidents from 2006 to 2011*

*Source: Compiled by author with data from (a) IMO report (2011) (b) Ukoji and Ukoji [35]*

Nigeria to provide timely and adequate compensation for insured risks. The study found that local insurers in Nigeria make arbitrary reserve funds for the compensation of insured risks, leading to insolvency challenges in compensating insured parties when insured risks occur. However, the study did not investigate the situation faced by seafarers in getting compensated by ship owners for injury and death costs affecting them during their work. Furthermore, it only focused on other classes and types of insurance trade without extending to marine employee liability insurance.

In a similar but distinct study, references [8] and [10] also obtained results akin to those of the IMF [4]. Reference [8] examined the ability of local underwriters to provide adequate compensation for offshore oil and gas risks. Its findings revealed that local underwriters lacked the sufficient capacity for the sustainable provision of compensation to affected parties in the sector. Similar to the IMF [4] study, this study did not consider marine employee liability insurance, which addresses the compensation of death and injury costs incurred by seafarers and other maritime workers. Reference [10] modeled the economic loss compensation for shipping accidents by local underwriters in Nigeria. The findings of this study also suggest a shortage of capacity for the appropriate and sustainable provision of compensation to affected shippers for insured shipping risks. Once again, the study did not consider seafarers as critical stakeholders in the shipping industry who also suffer injury and death costs due to marine accidents and must be compensated by ship owners in line with the provisions of the ILO.

Therefore, a gap exists in the literature whereby existing empirical studies seem to have failed to consider seafarers and other maritime workers as critical stakeholders in the maritime industry who bear the costs of injury and death associated with marine accidents. Given this gap, there is a lack of available empirical literature and knowledge on what constitutes the costs and burdens of injury and death suffered by Nigerian seafarers over the years and how or whether such costs have been compensated in accordance with the ILO's MLC, as existing empirical literature has focused more on identifying shortcomings in compensation for shippers and oil and gas industry operators only. Previous studies have also been unable to establish a basis for reserving adequate funds for the timely and sustainable provision of compensation for injury and death costs to affected seafarers by ship owners and marine underwriters.

The failure of existing empirical literature over the years to establish any knowledge and understanding of the economic costs incurred by maritime workers due to death and injury resulting from occupational (ship-based) accidents, as well as what constitutes the coefficients of the average rate of change of these costs, to guide marine underwriters in providing the necessary volume of funds to maintain financial solvency for the timely, adequate, and sustainable indemnification of insured maritime labor liability risks, constitutes the gap that this study has filled, contributing to the body of knowledge in this area of study in Nigeria.

## 4. Data and Methods

The study utilized an ex-post facto research design, employing time series secondary data. Secondary data was gathered on the number of seafarers who suffered from occupational-related illnesses, injuries, and deaths, for which ship owners are liable to compensate the affected seafarers. This data was obtained from the DPR Annual Statistical Report, the Fair Play database, and other secondary sources. In addition, data on per capita output in Nigeria was obtained from various editions of the Central Bank of Nigeria (CBN) Statistical Bulletin [37]. The time series data covered a 14-year period between 2006 and 2019 for each identified variable. The obtained data were analyzed using the GOM and Rate of Change Analysis (RCA) methods.

### 4.1. The Gross Output Model

The World Health Organization utilizes the GOM of the Human Capital model to assess the economic cost of fatalities and injuries resulting from work-related accidents that affect seafarers in Nigeria between 2006 and 2019. The objective is to estimate the annual cost burdens that ship owners in the economy are expected to compensate the illness and death affecting seafarers in their employment. Since ship owners are expected to employ risk transfer measures to fulfill these liabilities, the estimated injury and death costs will serve as empirical guides to maritime underwriters in determining the funds to be reserved for the adequate and sustainable indemnification of maritime labor liability costs in Nigeria.

According to the GOM, the cost of death is equal to the loss of output to the society that the victim of a fatal accident would have contributed to the economy if alive. Similarly, the economic cost of injury is equivalent to the loss of output that the injured person would have produced during hospitalization or injury-induced idle time. Reference [38] explains that valuing the economic costs of dead accident victims using the human capital approach involves considering the discounted value of people killed in the accident, as the loss of output is related to society and the nation.

By the GOM, life is valued as the total discounted value of expected and per capita outputs. Therefore, the gross output value represents the expected economic benefit to the economy from saving a life in a fatal marine accident or preventing an injury using safety shields, programs, and policies.

For a fatal marine accident involving death, the economic cost of output lost per death is determined as follows:

$$P_N = Y\left[\frac{1}{i}\right]\left[1-\frac{1}{(1+i)^t}\right] \quad (1)$$

Total output lost per period for several deaths =

$$= P_T = Y\left(\frac{1}{i}\right)\left(1-\frac{1}{(1+i)^t}\right)N \quad (2)$$

$P_N$= National output forgone per death due to marine accident

$P_T$= Total output forgone due to fatal marine accidents involving several deaths.

Y= Average (national) output or per capital output.

i= The social rate of discount (interest), which for developing countries tends towards 10 to 12, according to World bank records.

t= The number of working years lost per fatality, as defined by the difference between the retirement age in the public sector and the national average age of fatality in developing countries, approximates 25.2 to 29 years.

For injury accidents, the hospitalization period is considered one year unless the individual is permanently disabled and unable to work for the remainder of their lifetime. This duration is denoted as t=1.

The total number of deaths resulting from fatal marine accidents over a given period is represented by N.

Employing the aforementioned method and utilizing secondary data on seafarers who have experienced death due to work-related accidents, as well as per capita income, the expenses incurred by ship owners for injury and death compensation were assessed. This evaluation was carried out to determine the adequate funds required for the indemnification of maritime labor liability risks in Nigeria.

### 4.2. Rate of Change Analysis

We have estimated the coefficient for the average rate of change in the economic cost of occupational death and injury affecting seafarers. This estimation serves as the basis for projecting the provision of compensation funds to ensure adequate and sustainable compensation of maritime labor liability costs. In addition, we have calculated the average rate of change for each of the costs associated with death and injury over the 14-year period covered in this study. This empirical evidence supports the reservation of compensation funds for sufficient and sustainable indemnification of the risks associated with maritime labor liability, including death and injury costs.

In essence, the coefficient for the average rate of change from the interval $[t_1–t_{14}]$, which spans the 14-year period studied, can be estimated using the following expression:

$$\frac{\partial Y}{\partial t} = \frac{f(t1) - f(t14)}{t1 - t14} \quad (3)$$

For the economic cost of deaths, the coefficient of the average rate of change is determined as:

$$\frac{\partial ECdeath}{\partial t} = \frac{f(t1) - f(t14)}{t1 - t14} \quad (4)$$

For the economic cost of injury, the coefficient of the average rate of change over the period is determined as:

$$\frac{\partial ECinjury}{\partial t} = \frac{f(t1) - f(t14)}{t1 - t14} \quad (5)$$

where $f(t_1)$ and $f(t_{14})$ denote the variables corresponding to the first and last year's within the period covered in the study. It is important to note that utilizing Ordinary Least Square estimation, where the independent variable is the period [$t_1$-$t_{14}$], enables us to determine the trend of each variable over the study period, providing us with the regression coefficient as the average rate of change of each variable over the period covered in the analysis.

For the cost of death, the trend equation is:

$EC_{death} = \beta_0 + \beta_{1death} + e$

where e denotes the error term, t denotes the time, $\beta_{1death}$ denotes the coefficient of regression, $\beta_0$ denotes a constant. The coefficient of regression $\beta_{1death}$ represents the mean rate of change in the economic cost of mortality per unit of time within the studied period.

Thus, $$\frac{\partial ECdeat}{\partial t} = \frac{f(t1)\text{-}f(t14)}{t1\text{-}t14} = \beta_{1death} \quad (6)$$

The average rate of change in the economic cost of injuries resulting from marine accidents is illustrated below:

$$\frac{\partial ECinjury}{\partial t} = \frac{f(t1)\text{-}f(t14)}{t1\text{-}t14} = \beta_{1injury} \quad (7)$$

It is important to note that the empirical basis for determining a model of relationship that ensures an adequate volume of compensation fund reserved from the premium income of marine underwriters (MAPRE) for the compensation of maritime labor liability risks affecting ship owners and seafarers lies in the relationship between the mean value of output losses associated with each instance of injury/illness and death of seafarers, as well as the coefficient of the rate of change of the costs associated with each instance of injury and death.

## 4.3. Limitations of the Study

The secondary data utilized in this study were sourced from the CBN Statistical Bulletin, the DPR offshore/marine accident records, and Fair Play reports. However, it is plausible that certain ship accidents that affect seafarers and lead to injury, illness, or fatalities may go unreported, and consequently, the public may not be informed. Hence, the precision of the findings and estimations presented in this study may be somewhat impacted by the accuracy of the data accessed.

***Table 1.*** *Result showing the economic costs of injury and death associated with work-related injury and death affecting seafarers in Nigeria between 2006 and 2019, using GOM*

| s/n | $EC_{death}$ per annum = (USD) $= P_T = Y\left(\frac{1}{i}\right)\left(1 - \frac{1}{(1+i)^t}\right)N$ | Output lost per death (USD) $P_N = Y\left[\frac{1}{i}\right]\left[1 - \frac{1}{(1+i)^t}\right]$ | $EC_{injury} = P_i = Y\left(\frac{1}{i}\right)\left(1 - \frac{1}{(1+i)^t}\right)N$ (USD) |
|---|---|---|---|
| 2006 | 744,995.96 | 15,520.7 | 90,938.007 |
| 2007 | 3,477,416.79 | 17,648.02 | 247,486.644 |
| 2008 | 5,064,781.75 | 21,015.69 | 64,594.66 |
| 2009 | 297,727.18 | 17,721.86 | 59,577.21 |
| 2010 | 81,624.98 | 21,480.26 | 2,588,153.44 |
| 2011 | 278,670.55 | 23,616.15 | 77,124.24 |
| 2012 | 566,264.52 | 25,739.29 | 54,390.40 |
| 2013 | 1,118,058.25 | 28,091.92 | 105,232.26 |
| 2014 | 7,881,313.39 | 30,196.61 | 72,510.52 |
| 2015 | 179,088.90 | 25,584.13 | 115,497.19 |
| 2016 | 48,933.66 | 20,389.03 | 250,674.05 |
| 2017 | 51,647.14 | 18,445.41 | 53,151.12 |
| 2018 | 146,331.16 | 19,004.05 | 73,014.48 |
| 2019 | 54,323,605.70 | 20,893.69 | 56,192.22 |
| Total | 67,167,280.93 | | 3,908,536.44 |

Source: Authors calculation

## 5. Results and Discussion

The results on Table 1 above indicate the economic costs of maritime labor liability risks resulting from occupational accidents that affect seafarers in the Nigerian maritime sector. Ship owners are liable for these accidents. The aggregate cost of output losses due to the death of seafarers affected by occasional accidents over the study period is USD 67,167,280.93 equivalent to 26826610000 Nigerian naira at an exchange rate of 399.40 naira to 1 USD. On average, this amounts to output losses of 1,916,186,429 naira (4,797,662.92 USD) per year due to the death of seafarers affected by accidents in the Nigerian maritime sector. Therefore, the ship owners in the local industry must be able to compensate the affected workers with about 1916186429 NGN annually, per the MLC's provisions, 2006.

In the absence of a local P&I club in Nigeria and the capital-intensive nature of securing membership of foreign P&I clubs, local ship owners employ the risk transfer instruments available in the local insurance industry. Therefore, the local marine underwriting sector should develop the capacity to provide cover for marine labor liability claims resulting from the death of seafarers due to work-related accidents up to the tune of 1.9 billion naira per year in line with the provisions of the MLC 2006, as amended. Regulation 4.2 of the Convention makes it the liability of the ship owners to ensure that seafarers are protected from the financial consequences of work-induced sickness, injury, or death occurring in connexion with their employment. Item b of Regulation 4.2 expressly states that ship owners shall provide financial security to assure compensation in the event of the death or long-term disability of seafarers due to an occupational injury, illness, or hazard, as set out in national laws, the seafarers' employment agreement, or collective agreement. Regulation 4.2.1, paragraph 1(b), notes that the ship owner should subscribe to an insurance scheme or fund to meet maritime labor liability risks and ensure adequate compensation of seafarers in cases of death and injury arising from work-related accidents.

Similarly, the total economic cost and output losses resulting from the burden of injuries on seafarers due to work-related accidents in the Nigerian maritime sector during the study period amount to USD 3,908,536.44 (1561069454 NGN), with an average of USD 279,181.17 (111504961NGN) in output losses per year. Therefore, marine underwriters must develop the capacity to raise compensation funds for injury risks to USD 279,181.17 or above more annually to maintain financial solvency and ensure timely, adequate, and sustainable compensation for injury costs in Nigeria.

The average economic cost of maritime labor liability risks due to injury and death burdens affecting seafarers between 2006 and 2019 in Nigeria is USD 5,076,844.09 (1929200754 NGN) per year. It is important to note that estimating the coefficients of the average rate of change of both death and injury costs for which ship owners are liable can facilitate the development of empirical conditions and models of relationships that will ensure adequate and sustainable compensation for injury and death output losses affecting seafarers in Nigeria in the long run (Table 2).

The findings reveal that the mean rate of variation in the economic costs of death and injury liabilities for ship owners during the studied time frame is 1,399,708.265 USD and -29,587.87 USD, respectively, for each unit change in time (i.e. a one year increase). These results suggest an upward trend in output losses attributable to fatalities while simultaneously demonstrating a downward trend in the financial burden of injury costs. The model equations

***Table 2.*** *The coefficients of the average rate of change and implications for timely, adequate and sustainable compensation marine accidents injury cum death cost (maritime labor liability costs)*

| Variable | Mean | | $\frac{\partial Y}{\partial t}$ = average rate of change | ∂ t = Δt = unit change in time | Policy implication for sustainable compensation of maritime labor liability risks |
|---|---|---|---|---|---|
| | USD | N̶ | | | |
| $\boldsymbol{EC_{injury}}$ | 2,791,81.17 | 111504959 | - USD2958.876 | 1.0 | $MAPRE_{injury} \geq K$, where K = mean $EC_{injury}$.<br>or<br>decrease/$\Delta MAPRE_{injury} \leq \frac{\partial ECinjury}{\partial t}$<br>i.e.: $\Delta MAPRE_{injury} \leq$-USD29587.876 |
| $\boldsymbol{EC_{death}}$ | 5,304,318.57 | 2118544837 | USD1399708.265 | 1.0 | Increase/$\Delta MAPRE_{death} \geq \frac{\partial ECdeat}{\partial t}$[from mean $EC_{death}$]<br>i.e.: $\Delta MAPRE_{death} \geq 1399708.26$ from mean value of $EC_{death}$.<br>or<br>Where the preceding year value of $\boldsymbol{EC_{death}}$ is ($\boldsymbol{Y_d}$)>mean $\boldsymbol{EC_{death}}$;<br>Increase/$\Delta MAPRE_{death} \geq \frac{\partial ECdeat}{\partial t}$ [from $\boldsymbol{Y_d}$ ***value***]<br>i.e.: $\Delta MAPRE_{death} \geq 1399708.26$ from $Y_d$. |
| Source: Authors calculation | | | | | |

below provide a clearer illustration of the trends in death and injury costs, respectively:

$EC_{death} = -5193493.418 + 1399708.265T + e$

$EC_{injury} = 501090.244 - 29587.876T + e$

The impact and empirical implications of this on the development of a policy strategy for reserving funds to adequately and sustainably compensate maritime labor liability costs (including costs associated with death and injury) suggest that the compensation funds allocated for each type of maritime labor liability cost must increase in the same direction as changes in death and injury costs. In addition, to increase the confidence of maritime operators (i.e., ship owners) and stakeholders in the marine underwriting sector in relation to maritime employee liability insurance, in instances where there is an increasing trend in employee liability costs during any given period, the increase in compensation funds maintained by underwriters for maritime labor/employee liability costs within the same period must be greater than or proportional to the coefficient of the average rate of change of maritime labor liability costs.

Given that the coefficient of the average rate of change of economic costs associated with death affecting seafarers is 1,399,708.265 USD, as indicated in the above result, any increase in compensation funds maintained for the cost of death ($\Delta MAPRE_{death}$) must be greater than or proportional to 1,399,708.265 USD:

$$\Delta MAPRE_{death} \geq 1{,}399{,}708.265 \text{ USD} \quad (1)$$

The quantification of compensation funds necessary to provide prompt, sufficient, and lasting reimbursement for the financial impacts incurred by fatalities of seafarers as a result of work-related accidents per incremental change in time ($MAPRE_{deatht=1}$) equals the total of the average economic expense of mortality during the period or the previous year's economic cost of mortality ($Y_d$), whichever is greater.

i.e.: $MAPRE_{deatht=1} = \sum \text{Mean } EC_{death} + \frac{\partial ECdeath}{\partial t}]$ (2);

or

$$MAPRE_{deatht=1} = [\sum Y_d + \frac{\partial ECdeath}{\partial t}] \quad (3)$$

Where: $Y_d > \text{mean } EC_{death}$.

The implication is that underwriters responsible for compensating work-related deaths among seafarers in Nigeria must maintain a minimum compensation fund proportional to the mean value of USD 5304318.566. To ensure financial stability and timely, adequate, and sustainable compensation for ship owners' liability for work-related deaths, underwriters must increase compensation funds for death risks/liabilities by an amount equivalent to the coefficient of the average rate of change of economic cost of death over the study period, based on the mean and preceding year's economic cost of death values. This could impact the cost of purchasing marine insurance policies (premium) for maritime labor liability risks, as premiums may increase to enable timely and sustainable compensation.

The mean value of the cost of injury liability is USD 279181.1744, which implies that underwriters must reserve a minimum average compensation fund of USD 279,181.1744 for maritime labor injury costs. The results also indicate that the coefficient of the average rate of change of the cost of injury burden for which ship owners are liable over the study period is USD -29,587.876, indicating a decreasing trend in injury cost/liability. Therefore, to ensure timely, adequate, and sustainable compensation for work-related injuries affecting seafarers, compensation funds for injury liability ($MAPRE_{injury}$) must be proportional to or greater than the mean economic cost of injury.

$$MAPRE_{injury} \geq \text{mean USD } 279{,}181.1744 \quad (4)$$

Although the results indicate a decreasing trend in injury costs, it is advisable to reserve adequate compensation funds for injury liabilities to ensure financial solvency and sustainability. This can be achieved by reducing compensation funds reserved for injury liability by an amount proportional to or less than the coefficient of the average rate of change ($\Delta MAPRE_{injury} \leq$ USD -29587.876. However, it is recommended to maintain compensation fund reservations for injury costs within the condition that $MAPRE_{injury} \geq \text{mean } EC_{injury}$. This will provide the most secure and sustainable compensation for injury cost liabilities.

Policy Implications of the Coefficients of the Average Rate of Change of Death-cum-Injury Costs and Liabilities in Developing Strategies for the Reservation Funds for Compensation of Maritime Labor Liability Risks in Nigeria:

The results indicate that the average rate of change of the costs associated with death and injury liabilities of maritime operators during the study period were USD 1399708.265 and USD - 29587.87, respectively, for every unit increase in time (i.e. every year) within the study period. These results suggest an increasing trend in output losses due to work-related accidents resulting in the death of seafarers while also indicating a decreasing trend in the economic costs associated with injury burdens affecting seafarers. The respective average rate of change coefficients ($\partial Y/\partial t$) for death and injury costs are 1399708.265 and 29587.876. The implications of these results for the development of compensation funds to provide timely, adequate, and sustainable compensation for insured risks (death and injury costs) are significant. Specifically, the compensation funds reserved for each cost class (death or injury) must change in the same direction and proportionately with the coefficients of the average rate of change. If death and injury costs (maritime labor liability costs) increase, then the volume of compensation funds reserved to indemnify these costs must increase proportionately with the coefficients of the average rate of change. This condition will ensure that marine underwriters maintain financial solvency for timely and adequate indemnification of maritime labor liability risks (death and injury costs). With the coefficient of the average rate of change of economic cost of death accidents being USD 1399708.265, the change in compensation funds maintained for indemnification of the economic cost of death ($\Delta MAPRE_{death}$) must be greater than or proportional to 1,399,708.265 USD.

$\Delta MAPRE_{death} \geq 1{,}399{,}708.265$ *USD.*

The calculation for the compensation funds necessary to provide timely, sufficient, and sustainable indemnification for the economic burdens resulting from seafarers' deaths due to occupational accidents can be expressed as follows: $MAPRE_{deatht=1}$ equals the sum of the mean economic cost of death over the period and the preceding year's economic cost of death value ($Y_d$), whichever of the two is greater. It is important to note that this formula considers the unit increase in time.

$$MAPRE_{deatht=1} = \sum \textbf{Mean } EC_{death} + \frac{\partial ECdeath}{\partial t}];$$

or

$$MAPRE_{deatht=1} = [\sum Y_d + \frac{\partial ECdeath}{\partial t}]$$

where $Y_d > \textbf{mean } EC_{death}$.

By implication, underwriters must maintain compensation funds for death costs proportional to the mean value of USD 5,304,318.566 to ensure financial solvency and provide timely, adequate, and sustainable indemnification of death liabilities. To achieve this, underwriters must increase compensation funds for death liabilities by an amount equal to the rate of change of the economic cost of death over the period, based on the mean value and the preceding year's value of the economic cost of death. This may increase the cost of purchasing marine insurance policies for maritime labor liability risks, as insurance premiums may increase to ensure timely, adequate, and sustainable compensation payments.

The mean value of the economic cost of injury liability is USD 279,181.1744, indicating that the minimum average amount of compensation funds allowable for injury costs is USD 279,181.1744. The results also indicate that the average rate of change of the economic cost of injury over the study period is USD -29,587.876, indicating a decreasing trend in injury costs. Therefore, underwriters must ensure timely, adequate, and sustainable compensation for injury costs and liabilities by maintaining compensation funds for injury liability ($MAPRE_{injury}$) proportional to or greater than the mean economic injury cost.

That is: $MAPRE_{injury} \geq \textbf{mean } EC_{injury}$.

The results indicate a declining trend in injury costs over time, suggesting reducing the amount of compensation funds reserved for injury liability in proportion to or less than the average rate of change ($\Delta MAPRE_{injury} \leq$-29,587.876 USD) may be sufficient to adequately cover injury costs over the period. However, it is prudent to maintain compensation fund reserves for injury costs at a level where $MAPRE_{injury} \geq \textbf{mean } EC_{injury.}$ This approach ensures the greatest financial stability for underwriters and sustainable compensation for the costs associated with injury burdens borne by seafarers resulting from occupational accidents in Nigeria.

## 6. Conclusion

The estimated costs of death and injury burdens associated with occupational accidents affecting seafarers in Nigeria between 2006 and 2019 were an aggregate of USD 67,167,280.93 and USD 3,908,536.44, respectively. The average rate of change coefficients for death and injury costs were USD 1,399,708.265 and USD −29,587.876, respectively. These coefficients provide the basis for the development of empirical relationships to ensure the reservation of adequate funds. This is necessary to ensure that marine underwriters maintain solvency for timely, adequate, and sustainable compensation of maritime employee liabilities.

To ensure that ship owners and marine underwriters reserve sufficient funds for the sustainable compensation of costs associated with the death of seafarers in Nigeria, the amount of funds to be reserved per annum must satisfy the condition that $\Delta MAPRE_{death} \geq$USD 1,399,708.26. In addition, this amount must be based on the mean cost of death, which was USD 5,304,318.57 over the period.

Similarly, to ensure that ship owners and marine underwriters reserve adequate funds for the sustainable compensation of costs associated with injury to seafarers in Nigeria, the amount of funds to be reserved per annum must satisfy the condition that $\Delta MAPRE_{injury} \leq$USD -2,958.87. Furthermore, this amount must be based on the mean cost of injury, which was USD 279,181.17 over the period.

## 7. Recommendations

It is recommended, per the findings of the study, that:

(a) The compensation funds maintained for the economic cost of occupational deaths affecting seafarers in Nigeria must increase proportionately to the coefficient of the average rate of change of the economic cost of death over time. The recommended minimum increase in compensation funds is $\Delta MAPRE_{death} \geq$ *1,399,708.*265 USD*.* This is necessary to ensure that ship owners and marine underwriters can adequately compensate affected seafarers in the future.

(b) The amount of compensation funds required for the adequate indemnification of the cost of insured deaths for every unit increase in time ($MAPRE_{deatht=1}$) should be the sum of the mean economic cost of death over the period or the preceding year value of the economic cost of death ($Y_d$), whichever is greater.

$MAPRE_{deatht=1} = \sum \textbf{Mean EC}_{death} + \frac{\partial ECdeath}{\partial t}]$.

or, $MAPRE_{deatht=1} =[\sum Yd + \frac{\partial ECdeath}{\partial t}]$, where $Y_d > \textbf{mean EC}_{death}$.

The sole assurances to ensure that ship owners and marine underwriters can adequately compensate affected seafarers in the future are as follows.

(c) The compensation funds allocated for injury cost and liability ($MAPRE_{injury}$) should be proportional to or exceed the mean economic cost of injury, that is, $MAPRE_{injury} \geq$ $\textbf{mean EC}_{injury}$.

(d) The most prudent approach is to reserve compensation funds for injury costs under the condition that $MAPRE_{injury} \geq \textbf{mean EC}_{injury}$. This is the only guarantee that ship owners and marine underwriters have sufficient funds to compensate affected seafarers who may incur injury costs due to future marine accidents.

## 8. Suggestions for Further Studies

Given the projected economic costs associated with the death and injury burden imposed upon seafarers in the Nigerian maritime sector due to occupational accidents, it is imperative to conduct additional research to compare the costs of death and injury and to identify the vessel types that pose the greatest risk to seafarers. The outcome of the additional research will be valuable in prioritizing compliance with safety standards for specific vessel types, per the ILO's provisions for the living and working conditions onboard.

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# No Wind is Favorable Unless the Sailor is Participative: Customer Participation in Marina Services

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## Abstract

Marinas are essential for tourism as a customized service, which, in turn, necessitates active customer cooperation. This study investigates the participation behavior of customers in marina service delivery and aims to determine the facilitating factors and consequences of customer participation (CP). A questionnaire survey was performed to evaluate the perception of marina users (i.e., boat owners or captains) who received service from full-service private marinas. The collected data were analyzed using the generalized linear model. The empirical results showed that customer self-efficacy and customer affective trust are significant facilitating factors, and actionable participation is the most essential dimension of CP substantially impacting customer cocreated value. Moreover, "experience at sea" and "marina region" are the factors with high control effects on the relationships between CP, self-efficacy, trust, and cocreated value.

**Keywords:** Marina services, Customer participation, Service-dominant (S-D) logic, Value cocreation, Generalized linear model (GLM)

## 1. Introduction

Marinas are the most significant infrastructure facilities of marine tourism, which are defined as facilities operated for commercial purposes by public institutions or private enterprises located on the shores, providing shelter primarily for recreational boats at sea or on land with a mooring fee [1]. The Yacht Harbor Association defines marinas as facilities that provide leisure and recreational yachts with berthing space, have walkways for direct access to each boat, always have a sufficient water depth (including tide times), and offer car parking, shower-toilet, and other service units [2]. At present, marinas are becoming facilities where a wide variety of services, such as social life opportunities, shopping, sports, and health, are also offered. Compared with other types of services, marina services have highly sophisticated specifications, which require the utmost professionalism. Meeting the expectations of customers in marina services is becoming more difficult day by day because the competition is rapidly escalating [3]. Consequently, the involvement of the customer in the service processes and understanding their needs and expectations in marinas are vital details to be able to offer qualified services, create value for customers, and sustain long-term customer relations [4,5].

Customers' involvement in the service processes, also known as customer participation (CP), has long been the focus of attention in service research as it is the source of significant and valuable results for both the users and providers of the service [6,7]. CP refers to the involvement of service users in service processes by adding effort, knowledge, time, and other inputs [8,9]. CP provides productivity gains, improved quality, and customer satisfaction [10,11]. Therefore, as service-dominant (S-D) logic indicates, the customer can be considered an active resource participating in value creation. Customers are value cocreators along with service providers, and the value they create together is mostly realized and becomes prominent during service usage [12,13]. Therefore, service users' participation behaviors need to be examined to establish long-term sustainable relationships and create a shared value. Although many

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studies on CP, particularly on tourism and accommodation businesses (e.g., [14-17]), have been conducted, research in the field of marine tourism and marinas, which are one of the most important accommodation facilities, is limited. Hence, this study attempts to explore the CP concept in the marina industry and investigates the enablers and consequences of the participation behaviors of marina users. Quantitative research including constructs, such as customer trust, customer self-efficacy, CP, and customer cocreated value, was conducted with controlled variables, such as the region of the marina, customers' boat type, and customers' total experience at sea. This study aims to shed a light on the CP concept in the context of marina service delivery and provide feasible suggestions for marina service providers to ensure the participation of customers and achieve a cocreated value through service provision.

The succeeding section presents the theoretical background focusing on the constructs and proposes several hypotheses. Then, the methodology of this study and the results of the hypotheses are introduced. Subsequently, the methodology and results are discussed, highlighting the implications for theory and practice. Finally, the limitations and future research directions are provided.

## 2. Theoretical Background and Hypotheses

### 2.1. CP and Customer Trust

Ensuring the participation behavior of customers is among the basic principles of S-D logic [13]. This concept is the main theory of this research. It is "a service-centered alternative to the traditional goods-centered paradigm for understanding economic exchange and value creation that has been identified as an appropriate philosophical foundation for the development of service science" (p. 32) [18]. According to this principle, the customer has a participatory role and contributes to the service encounter as a value creator [13,19,20]. CP has been the sphere of interest in this research concerning service encounters for a long time. Chan et al. [21] explained CP as "the extent to which customers provide/share information, make suggestions, and become involved in decision-making" (p. 49). Effective CP increases the likelihood of meeting customers' expectations and needs by enabling the customers to obtain the benefit they are looking for [22]. In addition to increased quality levels, higher customized service and desired benefits enable customers to realize higher cocreated value levels about the service delivery [6,23]. Chen and Raab [24] divide CP behavior into three groups, namely, informational, attitudinal, and actionable. Informational participation means that the customer makes an effort to obtain information about the services from several sources. Attitudinal participation involves the customer's behavior toward the service provider during service encounters, such as being cooperative and friendly. Actionable participation explains the customer's tendency to ask questions or intervene in the service delivery process [24].

Customer trust is a building block of relationships and plays an important part in relationship commitment [25]. If the customer is convinced that the service provider is truthful and candid, then they will be willing to participate in their service delivery and provide information about their expectations regarding their needs [26,27]. Consistent with S-D logic, tangible and intangible resources are exchanged between customers and service providers, and trust between these two parties is a necessary component of their relationship [28]. Trust enhances customers' willingness to participate and cooperate in the service delivery process [29,30]. Furthermore, Etgar [31] argued that, if the service provider does not exhibit opportunistic behavior according to customers' perception, then this will encourage the customers to participate more in coproduction processes. The study conducted by Luk et al. [26] showed that customer trust in service organizations encourages customers to become a part of service production/delivery processes and that customers also contribute to value creation and efficiency by using the service. Shen et al. [32] empirically demonstrated that trust enhances the perceived cocreated value of customers and their willingness to participate.

In marina marketing settings, customer relations and active contact with customers are substantial [4], and customer trust can be an important antecedent concept that leads marina users to increase their participation. For this reason, in this study, the effect of customer trust on the customers' tendency to participate in marina service delivery processes will be investigated. Customer trust is divided into two groups, namely, cognitive and affective. "Cognitive trust" in a firm might have its roots in the knowledge and competencies of the service provider [33], whereas "affective trust" is based on customer evaluations consistent with service experiences and represents emotion-driven confidence in a service organization [34,35]. The following hypotheses were proposed:

H1: Customer trust positively affects CP behavior.

H1a: Affective trust positively affects (1) attitudinal, (2) informational, and (3) actionable participation behaviors.

H1b: Cognitive trust positively affects (1) attitudinal, (2) informational, and (3) actionable participation behaviors.

### 2.2. CP and Customer Self-efficacy

Self-efficacy is "a judgment of one's capability to accomplish a certain level of performance" (p. 94) [36]. Self-efficacy represents the customers' judgments of their capabilities to perform a task in service production and delivery processes [37,38]. Thus, while maintaining effective relationships and cocreating value consistent with S-D logic, these factors need to be considered during service exchanges [39,40]. This concept has also been empirically measured as an enabler of CP behavior. For instance, Chen and Raab [24] advocated that self-efficacy significantly influences customers' participation behaviors. Chen et al. [41] also measured the facilitating effect of customer self-efficacy on the dimensions of CP and empirically demonstrated that participation behavior is significantly facilitated by self-efficacy. According to Im and Qu [15], having a greater self-efficacy encourages customers to participate, and the link between customer knowledge and cocreation is mediated by self-efficacy. Zhao et al. [42] empirically demonstrated that customer self-efficacy enhances the perceived value of customers and their eagerness to voluntarily be a part of value creation activities. Moreover, marina services belong in the luxury service group, and most of their users already have extensive knowledge about these services, which may lead to an increase in their self-efficacy perceptions. This high perception of self-efficacy can lead service users to participate more. Therefore, the following hypotheses were proposed:

H2: Self-efficacy positively affects CP behavior.

H2a: Self-efficacy positively affects attitudinal participation behavior.

H2b: Self-efficacy positively affects informational participation behavior.

H2c: Self-efficacy positively affects actionable participation behavior.

### 2.3. Customer Participation and Customer Cocreated Value

From a customer-oriented approach, cocreated value refers to "a personal appraisal of the meaningfulness of a target (product or service, further referred to as service) based on what is contributed and what is realized through the process of cocreation" (p. 70) [43]. As a result of service experience and service usage, the value is perceived and cocreated by customers [26,44,45]. Prior studies have empirically demonstrated the facilitating effect of participation behavior from customers on cocreated value in service delivery [6,46]. The study conducted by Chan et al. [21] is among the pioneering research that evaluates the relationship between CP and customer value creation. They demonstrated the positive effects of CP on economic and relational values. Similarly, Chen and Wang [47] reported the positive effects of CP on both intrinsic (enjoyment) and extrinsic (relational and economic) value types. Taheri et al. [16] also proposed two different cocreated value concepts, i.e., economic and relational value, similar to the categories in the study conducted by Chan et al. [21], and demonstrated the influence of CP on the cocreated value of customers. Chen and Chen [48] also reported the influence of customers' participation behavior on relational value as a cocreated customer value in the service delivery process.

Marina services are expensive services; therefore, customers adopt a more participatory approach to obtain more economic value. Furthermore, given that the time spent in the marina is generally for leisure activities, customers need to enjoy themselves during that time and have a good relationship with the marina service providers. Thus, customers are more likely to participate in service delivery processes. In summary, the cocreated value of marina customers may be an outcome of their participation behavior, and this value probably includes economic benefits and relational bonds [21,49]. Thus, the following hypotheses were proposed:

H3: CP behavior positively affects customer cocreated value.

H3a: Attitudinal participation behavior positively affects (1) economic and (2) relational values.

H3b: Informational participation behavior positively affects (1) economic and (2) relational values.

H3c: Actionable participation behavior positively affects (1) economic and (2) relational values.

## 3. Methodology

### 3.1. Survey Development and Measures

To measure the research constructs, items were adopted from previous studies. The participation behavior of customers was measured according to the scale developed by Chen and Raab [24]. The scale is composed of three subdimensions, namely, informational participation, actionable participation, and attitudinal participation, with each subdimension having three items. The customer trust scale of Schumann et al. [50] was used to measure the trust of marina service users. Their scale has two subdimensions, namely, cognitive trust and affective trust. Each dimension has four items. Customer self-efficacy was borrowed from Chen and Raab [24] and measured with three items. Finally, the customer cocreated value was measured according to the scale used in the study conducted by Yim et al. [38]; the scale has 12 items and reflects the two components of cocreated value, namely, economic and relational (Figure 1).

All items were measured using a five-point Likert scale ranging from "strongly disagree" (1) to "strongly agree" (5). This study also has four control variables involving the region of the marina from which the customer obtains services, the customer's boat type, and the customer's total experience at sea. Ethical approval for this study was waived

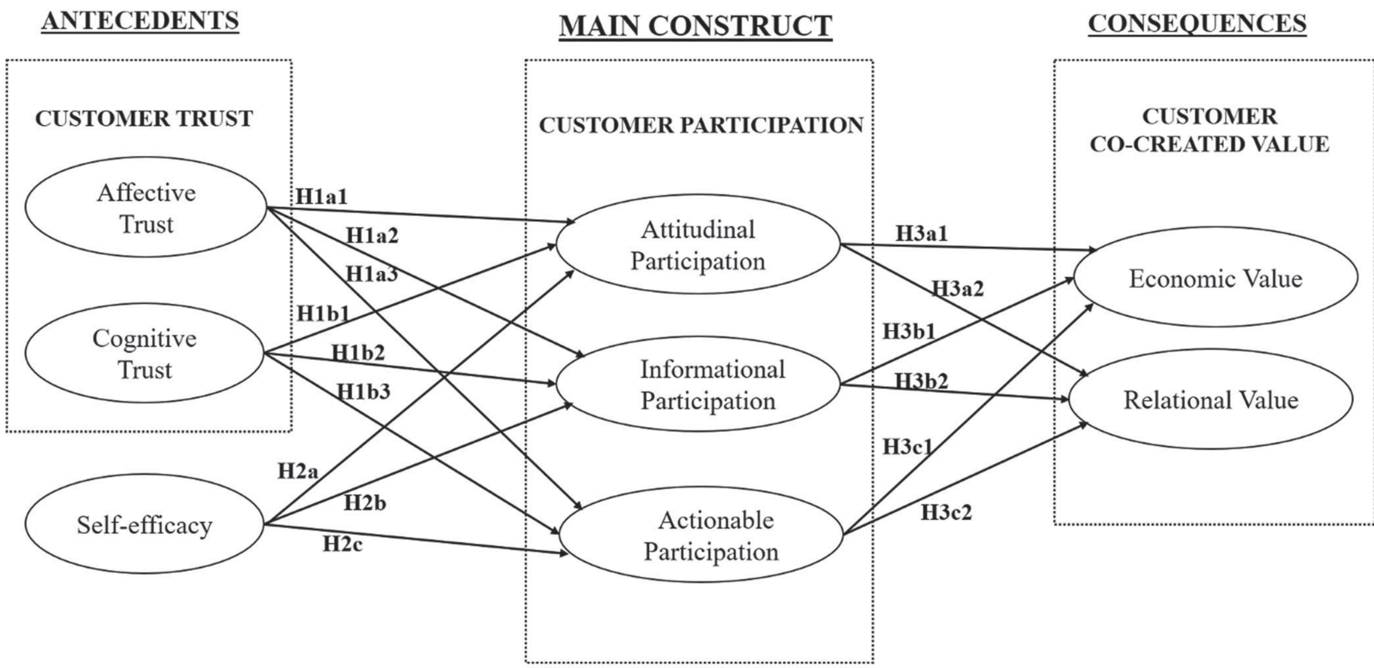


***Figure 1.*** *Conceptual model of the main study*

by the Dokuz Eylül University Ethical Committee (approval number: 87347630/42104268/1079).

### 3.2. Sampling and Data Collection

The sample for this study consists of marina users (i.e., boat owners or captains) who received service from full-service private marinas on the Western Coast of Türkiye between Ayvalik and Fethiye. In 2021, approximately 70% of the 152,765 yachts and 60% of the yachtsmen and crew (a total of 1,231,254 people) arrived in the country and visited the marinas in this region [51]. A large number of marinas were visited for this study. However, the companies did not want to share any information about the number of yachts moored or the yachts with captains. Given that this information is not recorded anywhere, a judgmental (purposive) sampling technique, which is one of the non-probability sampling methods, was employed in this study. In this method, the researchers include elements with certain characteristics that they consider suitable for research purposes based on their observations [52,53]. Therefore, the most well-known regions where the most intense yachting activities occur in Türkiye between Ayvalık and Fethiye were visited. While walking around the marina area, the answers of the people identified as receiving services from the marina and determined to have a level of knowledge about the services were included in this study.

Most of the marinas visited are in Muğla, and the 14 largest marinas in the country are in the Marmaris, Bodrum, and Fethiye-Göcek districts of this province. This city has a capacity of approximately 7,000 yachts, whereas Türkiye has a total mooring capacity of 24,000 both onshore and at sea. Furthermore, the North and Middle Aegean Marinas located in the provinces of Aydın, İzmir, and Balıkesir, which are also visited, have become essential attraction centers for yachting activities, particularly with the recently opened facilities. This information also supports our purposive sampling method. Questionnaire collection was conducted in 12 marinas (Appendix 1). The first researcher visited these marinas between January and April of 2020 within the scope of her Ph.D. dissertation. The survey collection process was conducted face-to-face and online with the kind support of the marina managers and other employees. The survey was answered in approximately 10-15 min.

The listwise deletion (complete case analysis) technique is used to handle missing data [54,55]. Thus, 19 responses to the questionnaire collected from participants were removed, resulting in a total of 602 usable questionnaires in the final data set: 120 from Marmaris Marinas, 120 from Bodrum Marinas, 152 from Fethiye-Göcek Marinas, 210 from North and Middle Aegean Marinas (Aydın-İzmir-Balıkesir/Ayvalık).

Among the 602 respondents, 84.39% (n=508) are male and 15.61% (n=94) are female. A total of 511 respondents (84.88%) are Turkish, whereas 91 (15.12%) respondents are from other nationalities (i.e., British, Russian, and Italian). Of the respondents, 32.72% (n=197) declared that they are high school graduates, whereas 41.86% (n=252) graduated from a vocational higher school or university. Of the respondents, 19.44% (n=117) have Master's and

Doctorate degrees. In terms of age distribution, as shown in Table 1, the majority of the participants (46.35%) are over 46 years old.

## 4. Analysis and Results

Before hypothesis testing, reliability and validity analyses of the survey were performed. A normality test was performed using the Kolmogorov-Smirnov test to obtain the scale scores. Because the scale scores were not normally distributed, nonparametric analyses were conducted. Spearman's rho correlation was used for relational analysis. The generalized linear model (GLM), a nonparametric regression analysis, was also used to identify causality relationships between the constructs and test the hypotheses.

As mentioned previously, the parameters were distorted because of contradictory observations. Although outliers were excluded from this study, parametric methods did not produce an appropriate analysis, but nonparametric regression provided a solution [56]. This regression method, which is the opposite of the parametric approach, tried to analyze the relationships between dependent and independent variables without considering any functional form of the model [57]. This regression method was first introduced by Nelder and Wedderburn [58], and it is an extension of the GLM. Moreover, this regression method broadens the scope of linear statistics usage by "accommodating response variables with non-normal conditional distributions" [59]. GLM is a generalization of classical linear models. In other words, this model associates a nonlinear population with a linear predictor that has a link function. This model also ensures the

***Table 1.*** *Demographic characteristics of the sample*

| Variable | Category | Frequency (N=602) | Percentage (%) |
|---|---|---|---|
| Age | 18-24 | 29 | 4.82 |
| | 25-31 | 73 | 12.13 |
| | 32-38 | 110 | 18.27 |
| | 39-45 | 111 | 18.44 |
| | 46 and above | 279 | 46.35 |
| Gender | Female | 94 | 15.61 |
| | Male | 508 | 84.39 |
| Nationality | Turkish | 511 | 84.88 |
| | Other | 91 | 15.12 |
| Education | Elementary school | 36 | 5.98 |
| | High school | 197 | 32.72 |
| | Vocational higher school | 73 | 12.13 |
| | Undergraduate | 179 | 29.73 |
| | Postgraduate | 117 | 19.44 |

exponential distribution of dependent variables [60]. Thus, GLM consists of three main components [58,59]:

**(i)** *A dependent variable* (random component or expected response) that has an exponential distribution ($Y_i$).

**(ii)** *A set of independent variables* called a linear predictor:

$\eta_i = \alpha + \beta_1 X_{i1} + \ldots + \beta_k X_{ik}$.

The expected value $\mu_i$ of $Y_i$ depends on it. $X$ denotes the transformation of predictors, such as polynomial terms and logarithmic alterations.

**(iii)** *A linking function* (*mean function*) that changes the expectation of the dependent variable to the linear predictor (independent variable):

$g(\mu_i) = \eta_i$.

Confirmatory factor analysis (CFA) was performed using AMOS 24.0. Other analyses were performed using SPSS 25.0 for Windows at a 95% confidence interval.

### 4.1. Assessment of Normality

The Kolmogorov-Smirnov test was used to assess the distributional adequacy of the collected data [61]. The normality test analysis results indicated that not all scale parameter distributions were normally distributed, as shown in Appendix 2 ($p<0.05$). The normality of the data is a requirement for the parametric tests. Thus, one of the nonparametric tests, i.e., generalized linear regression, was used in hypothesis analysis [62].

### 4.2. Reliability and Validity of the Scales

To measure reliability, Cronbach's alpha and composite reliability (CR) values were calculated in this study. The Cronbach's alpha values of the scales ranged from 0.654 to 0.925, indicating reliability that is within acceptable limits [63,64]. Moreover, the reliability of each item was revealed by item-total correlation. All of the values of the items in the questionnaire were not less than 0.3, which is the recommended cutoff value [65]. In the beginning, for the affective dimension of the trust scale, Cronbach's alpha level was 0.237, which was unacceptable for reliability. Scales of items with deleted results showed that item 2 in the affective dimension caused a reduction of internal consistency, as shown in Appendix 3. Thus, Item 2 for the affective scale dimension (AFT_2: "This marina pursues predominantly egoistic aims") was excluded from the scale; consequently, the value increased to 0.796. Furthermore, CR values were calculated to evaluate the internal consistency of the scales [66,67]. CR values ranging from 0.78 to 0.91 were also greater than the recommended threshold level of acceptance (i.e., 0.70) [68].

CFA and average variance extracted (AVE) calculations were performed to confirm the validity of the constructs [63]. As shown in Appendix 4, the fit indices of each variable have acceptable values. Because of the lack of subdimensions, goodness-of-fit indices could not be calculated individually for the customer self-efficacy scale (Appendix 4) [69]. The CFA results of this study are presented in Table 2. The factor loadings ranged from 0.538 to 0.910 and provided an acceptable level, which is 0.5 [63]. The CFA findings also supported the decision to reduce the item of affective trust (Item 2). The factor weight of Item 2 (AFT2) was -553, which was less than the acceptable level. Moreover, the findings confirmed that all AVE values of the scales ranged from 0.55 to 0.72, which were greater than the cutoff value [66,68].

***Table 2.*** *Confirmatory factor analysis results*

| Constructs and items | Factor loading | S.E. | t value | p | Cronbach's alpha | CR | AVE |
|---|---|---|---|---|---|---|---|
| **Customer trust** | | | | | **0.908** | | |
| **Affective trust** | | | | | 0.796 | **0.82** | **0.61** |
| AFT1 | 0.735 | - | - | - | | | |
| AFT3 | 0.711 | 0.071 | 15.985 | *** | | | |
| AFT4 | 0.836 | 0.064 | 18.038 | *** | | | |
| **Cognitive trust** | | | | | 0.925 | **0.91** | **0.72** |
| COGT1 | 0.869 | - | - | - | | | |
| COGT2 | 0.908 | 0.032 | 31.346 | *** | | | |
| COGT3 | 0.903 | 0.033 | 31.007 | *** | | | |
| COGT4 | 0.800 | 0.034 | 24.817 | *** | | | |
| **Customer self-efficacy** | | | | | **0.762** | **0.864** | **0.679** |
| SE1 | 0.649 | - | - | - | | | |
| SE2 | 0.862 | 0.103 | 12.298 | *** | | | |
| SE3 | 0.657 | 0.074 | 12.899 | *** | | | |
| **Customer participation** | | | | | **0.756** | | |
| **Attitudinal participation** | | | | | 0.771 | **0.85** | **0.66** |
| CPAT1 | 0.615 | - | - | - | | | |
| CPAT2 | 0.910 | 0.089 | 13.812 | *** | | | |
| CPAT3 | 0.722 | 0.062 | 13.984 | *** | | | |
| **Informational participation** | | | | | 0.713 | **0.82** | **0.63** |
| CPINF1 | 0.548 | - | - | - | | | |
| CPINF2 | 0.697 | 0.135 | 10.741 | *** | | | |
| CPINF3 | 0.785 | 0.152 | 10.657 | *** | | | |
| **Actionable participation** | | | | | 0.654 | **0.782** | **0.55** |
| CPAC1 | 0.538 | - | - | - | | | |
| CPAC2 | 0.624 | 0.120 | 9.824 | *** | | | |
| CPAC3 | 0.737 | 0.107 | 9.594 | *** | | | |
| **Customer cocreated value** | | | | | **0.900** | | |
| **Economic value** | | | | | 0.830 | **0.84** | **0.63** |
| ECOV1 | 0.799 | - | - | - | | | |
| ECOV2 | 0.730 | 0.063 | 18.402 | *** | | | |
| ECOV3 | 0.852 | 0.053 | 21.641 | *** | | | |
| **Relational value** | | | | | 0.892 | **0.88** | **0.70** |
| RELV1 | 0.875 | - | - | - | | | |
| RELV2 | 0.810 | 0.039 | 24.677 | *** | | | |
| RELV3 | 0.889 | 0.035 | 28.445 | *** | | | |

*p<0.001

All items were measured using the five-point Likert scale (1= strongly disagree; 5= strongly agree). CR: Composite reliability, AVE: Average variance extracted

### 4.3. Hypothesis Testing

In this study, H1, H2, and H3 were analyzed. To test these hypotheses, the Wald test of the concentration parameter is used to estimate the (approximate) p value [70].

#### 4.3.1. Influence of Customer Trust on CP Behavior

The GLM findings regarding H1 are shown in Tables 3 and 4. Affective customer trust significantly and positively affected attitudinal ($B$=0.260; p<0.01), informational ($B$=0.144; p<0.01), and actionable ($B$=0.193; p<0.01) participation behaviors. The regression coefficients also indicated that the greatest impact was on attitudinal participation behavior, followed by actionable and informational participation behaviors. Two categories of experience (i.e., 3-5 and 9-11 years) and one category of marina region (i.e., Marmaris) significantly influenced the relationship between affective trust and attitudinal participation (p<0.05). Furthermore, the first category of experience (i.e., 2 years and below) positively influenced the relationship between affective trust and informational participation (p<0.05).

The results also indicated that cognitive customer trust significantly and positively influenced the attitudinal ($B$=0.15; p<0.01) and actionable ($B$=0.12; p<0.01) dimensions of CP, whereas the effect on informational participation was insignificant (p>0.01). Moreover, the control variable results indicated that two categories of experience (i.e., 3-5 and 9-11 years) and two categories of marina region (i.e., Marmaris and Ayvalık) had significant

***Table 3.*** *Generalized linear model (GLM) results for affective trust and subdimensions of customer participation (CP)*

| Parameter | Attitudinal | | | | Informational | | | | Actionable | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | B | Std. error | $\chi^2$ | p | B | Std. error | $\chi^2$ | p | B | Std. error | $\chi^2$ | p |
| (Intercept) | 10.86 | 0.34 | 993.323 | 0.000 | 9.434 | 0.5386 | 306.813 | 0.000 | 10.431 | 0.4128 | 638.389 | 0.000 |
| **[Experience 1]** (2 years and below) | 0.01 | 0.32 | 0.001 | 0.977 | 1.198 | 0.5013 | 5.711 | **0.017** | -0.286 | 0.3842 | 0.555 | 0.456 |
| **[Experience 2]** (3-5 years) | -0.58 | 0.20 | 8.284 | **0.004** | -0.412 | 0.3124 | 1.740 | 0.187 | -0.228 | 0.2395 | 0.909 | 0.340 |
| **[Experience 3]** (6-8 years) | -0.10 | 0.20 | 0.249 | 0.617 | 0.461 | 0.3121 | 2.186 | 0.139 | -0.155 | 0.2393 | 0.418 | 0.518 |
| **[Experience 4]** (9-11 years) | -0.60 | 0.20 | 9.213 | **0.002** | -0.053 | 0.3091 | **0.029** | 0.864 | 0.180 | 0.2369 | 0.578 | 0.447 |
| **[Experience 5]** (12 years and above) | 0[a] | . | . | . | 0[a] | . | . | . | 0[a] | . | . | . |
| **[Type 1]** (M/Y) | 0.06 | 0.16 | 0.158 | 0.691 | -0.023 | 0.2463 | **0.009** | 0.925 | 0.223 | 0.1888 | 1.393 | 0.238 |
| **[Type 2]** (S/Y) | 0[a] | . | . | . | 0[a] | . | . | . | 0[a] | . | . | . |
| **[Region 1]** (Bodrum) | 0.09 | 0.20 | 0.210 | 0.647 | 0.232 | 0.3133 | **0.546** | 0.460 | -0.212 | 0.2402 | 0.781 | 0.377 |
| **[Region 2]** (Fethiye-Göcek) | 0.25 | 0.19 | 1.687 | 0.194 | 0.027 | 0.2990 | **0.008** | 0.929 | -0.408 | 0.2292 | 3.168 | 0.075 |
| **[Region 3]** (Marmaris) | -0.51 | 0.20 | 6.591 | **0.010** | 0.092 | 0.3106 | **0.087** | 0.768 | -0.065 | 0.2381 | 0.074 | 0.786 |
| **[Region 4]** (Ayvalık) | 0.39 | 0.25 | 2.425 | 0.119 | 0.565 | 0.3910 | 2.086 | 0.149 | 0.539 | 0.2997 | 3.236 | 0.072 |
| **[Region 5]** (İzmir-Aydın) | 0[a] | . | . | . | 0[a] | . | . | . | 0[a] | . | . | . |
| **CT affective** | **0.260** | **0.03** | **99.206** | **0.000** | **0.144** | **0.0400** | **12.937** | **0.000** | **0.193** | **0.0307** | **39.448** | **0.000** |
| (Scale) | 2.583[b] | 0.15 | | | 6.315[b] | 0.3640 | | | 3.710[b] | 0.2139 | | |

Dependent variable(s): CP_Attitudinal, CP_informational, CP_actionable
Model: (Intercept), Experience, Position, Type, Region, CT_affective
[a]Reference category, [b]Maximum likelihood estimate

effects on the relationship between affective trust and attitudinal participation ($p<0.05$). One category of marina region (i.e., Ayvalık) also significantly influenced the relationship between cognitive trust and actionable participation ($p<0.05$). Consequently, sub-hypotheses H1a1, H1a2, H1a3, H1b1, and H1b3 were supported, whereas sub-hypothesis H1b2 was rejected.

### 4.3.2. Influence of Customer Self-efficacy on CP Behavior

Table 5 shows that self-efficacy significantly and positively impacted attitudinal ($B$=0.498; $p<0.01$), informational ($B$=0.294; $p<0.01$), and actionable ($B$=0.447; $p<0.01$) participation. The most significant effect was on attitudinal participation, followed by actionable and informational participation. The control variables indicated that the fourth category of experience (i.e., 9-11 years) and the second category of marina region (i.e., Fethiye-Göcek) significantly influenced the relationship between self-efficacy and attitudinal participation ($p<0.05$).

The first category of experience (i.e., 2 years and below) also significantly and positively influenced the relationship between self-efficacy and informational participation ($p<0.05$). Thus, the sub-hypotheses of H2 were supported.

### 4.3.3. Influence of CP Behavior on Customer Cocreated Value

The customer attitudinal participation and subdimensions of customer cocreated value results are shown in Table 6. Customer attitudinal participation was positively correlated with economic ($B$=0.414; $p<0.01$) and relational ($B$=0.545; $p<0.01$) dimensions of customer cocreated value. The regression coefficients proved that its influence on relational value is higher than that on economic value. Moreover, no categories of control variables affect the way attitudinal participation and customer cocreated value are related ($p>0.05$). Consequently, sub-hypotheses H3a1 and H3a2 were supported.

Table 7 shows the causality relationship between customer informational participation and subdimensions of customer cocreated value. Informational participation positively influenced the economic ($B$=0.164; $p<0.01$) and relational ($B$=0.216; $p<0.01$) dimensions of customer cocreated

***Table 4.*** *GLM results for cognitive trust and subdimensions of CP*

| Parameter | Attitudinal | | | | Informational | | | | Actionable | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $B$ | Std. error | $\chi^2$ | p | $B$ | Std. error | $\chi^2$ | p | $B$ | Std. error | $\chi^2$ | p |
| (Intercept) | 11.49 | 0.35 | 1,073.285 | 0.000 | 10.28 | 0.54 | 366.706 | 0.000 | 10.86 | 0.41 | 693.096 | 0.000 |
| **[Experience 1]** (2 years and below) | -0.03 | 0.33 | 0.008 | 0.929 | 1.18 | 0.51 | 5.484 | 0.019 | -0.32 | 0.39 | 0.662 | 0.416 |
| **[Experience 2]** (3-5 years) | -0.56 | 0.21 | 7.483 | **0.006** | -0.39 | 0.32 | 1.512 | 0.219 | -0.22 | 0.24 | 0.833 | 0.361 |
| **[Experience 3]** (6-8 years) | -0.08 | 0.21 | 0.157 | 0.692 | 0.49 | 0.31 | 2.398 | 0.122 | -0.14 | 0.24 | 0.346 | 0.556 |
| **[Experience 4]** (9-11 years) | -0.66 | 0.20 | 10.474 | **0.001** | -0.09 | 0.31 | 0.074 | 0.785 | 0.14 | 0.24 | 0.322 | 0.571 |
| **[Experience 5]** (12 years and above) | 0[a] | . | . | . | 0[a] | . | . | . | 0[a] | . | . | . |
| **[Type 1]** (M/Y) | 0.00 | 0.16 | 0.001 | 0.981 | -0.05 | 0.25 | 0.047 | 0.829 | 0.17 | 0.19 | 0.812 | 0.367 |
| **[Type 2]** (S/Y) | 0[a] | . | . | . | 0[a] | . | . | . | 0[a] | . | . | . |
| **[Region 1]** (Bodrum) | 0.04 | 0.21 | 0.033 | 0.856 | 0.26 | 0.32 | 0.647 | 0.421 | -0.26 | 0.24 | 1.117 | 0.291 |
| **[Region 2]** (Fethiye-Göcek) | 0.34 | 0.20 | 3.037 | 0.081 | 0.09 | 0.30 | 0.098 | 0.755 | -0.34 | 0.23 | 2.145 | 0.143 |
| **[Region 3]** (Marmaris) | -0.66 | 0.21 | 10.475 | **0.001** | 0.03 | 0.31 | 0.010 | 0.919 | -0.18 | 0.24 | 0.581 | 0.446 |
| **[Region 4]** (Ayvalık) | 0.59 | 0.26 | 5.337 | **0.021** | 0.67 | 0.39 | 2.920 | 0.087 | 0.69 | 0.30 | 5.274 | **0.022** |
| **[Region 5]** (İzmir) | 0[a] | . | . | . | 0[a] | . | . | . | 0[a] | . | . | . |
| **CT cognitive** | **0.15** | **0.02** | **59.352** | **0.000** | **0.05** | **0.03** | **3.115** | **0.078** | **0.12** | **0.02** | **25.874** | **0.000** |
| (Scale) | 2.739[b] | 0.16 | | | 6.417[b] | 0.37 | | | 3.790[b] | 0.22 | | |

Dependent Variable(s): CP_Attitudinal, CP_informational, CP_actionable
Model: (Intercept), Experience, Position, Type, Region, CT_cognitive
[a]Reference category, [b]Maximum likelihood estimate

***Table 5.*** *GLM results for customer self-efficacy and subdimensions of CP*

| Parameter | Attitudinal | | | | Informational | | | | Actionable | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***B*** | **Std. error** | $\chi^2$ | **p** | ***B*** | **Std. error** | $\chi^2$ | **p** | ***B*** | **Std. error** | $\chi^2$ | **p** |
| (Intercept) | 6.986 | 0.5268 | 175.872 | 0.000 | 7.077 | 0.8651 | 66.914 | 0.000 | 6.920 | 0.6452 | 115.015 | 0.000 |
| **[Experience 1]** (2 years and below) | 0.120 | 0.3027 | 0.158 | 0.691 | 1.264 | 0.4970 | 6.463 | **0.011** | -0.192 | 0.3707 | 0.269 | 0.604 |
| **[Experience 2]** (3-5 years) | -0.132 | 0.1901 | 0.482 | 0.488 | -0.153 | 0.3121 | 0.241 | 0.624 | 0.137 | 0.2328 | 0.344 | 0.557 |
| **[Experience 3]** (6-8 years) | -0.037 | 0.1882 | 0.040 | 0.842 | 0.496 | 0.3091 | 2.574 | 0.109 | -0.110 | 0.2305 | 0.228 | 0.633 |
| **[Experience 4]** (9-11 years) | -0.578 | 0.1866 | 9.602 | **0.002** | -0.039 | 0.3064 | 0.016 | 0.899 | 0.203 | 0.2285 | 0.791 | 0.374 |
| **[Experience 5]** (12 years and above) | 0[a] | . | . | . | 0[a] | . | . | . | 0[a] | . | . | . |
| **[Type 1]** (M/Y) | -0.082 | 0.1489 | 0.300 | 0.584 | -0.107 | 0.2445 | 0.193 | 0.661 | 0.104 | 0.1823 | 0.328 | 0.567 |
| **[Type 2]** (S/Y) | 0[a] | . | . | . | 0[a] | . | . | . | 0[a] | . | . | . |
| **[Region 1]** (Bodrum) | 0.154 | 0.1884 | 0.665 | 0.415 | 0.263 | 0.3094 | 0.721 | 0.396 | -0.178 | 0.2308 | 0.594 | 0.441 |
| **[Region 2]** (Fethiye-Göcek) | 0.564 | 0.1802 | 9.807 | **0.002** | 0.209 | 0.2959 | 0.499 | 0.480 | -0.156 | 0.2207 | 0.498 | 0.480 |
| **[Region 3]** (Marmaris) | -0.357 | 0.1879 | 3.608 | 0.058 | 0.183 | 0.3086 | 0.350 | 0.554 | 0.066 | 0.2302 | 0.083 | 0.773 |
| **[Region 4]** (Ayvalık) | 0.297 | 0.2362 | 1.583 | 0.208 | 0.506 | 0.3879 | 1.702 | 0.192 | 0.447 | 0.2893 | 2.387 | 0.122 |
| **[Region 5]** (İzmir) | 0[a] | . | . | . | 0[a] | . | . | . | 0[a] | . | . | . |
| **Self-efficacy** | **0.498** | **0.0365** | **185.540** | **0.000** | **0.294** | **0.0600** | **23.938** | **0.000** | **0.419** | **0.0447** | **87.708** | **0.000** |
| (Scale) | 2.300[b] | 0.1326 | | | 6.204[b] | 0.3576 | | | 3.451[b] | 0.1989 | | |

Dependent variable(s): CP_Attitudinal, CP_informational, CP_actionable
Model: (Intercept), Experience, Position, Type, Region, Self-efficacy
[a]Reference category, [b]Maximum likelihood estimate

value. Therefore, sub-hypotheses H3b1 and H3b2 were also supported. However, the control variables did not significantly impact the relationship between customer informational participation and customer cocreated value ($p>0.05$).

The results for actionable participation indicated its significant positive impact on the economic ($B$=0.522; $p<0.01$) and relational ($B$=0.505; $p<0.01$) cocreated values (see Table 8). The regression coefficients verified that the influence of actionable participation on relational value is lower than that on economic value. Furthermore, no categories of control variables affected the way actionable participation and customer cocreated value were related ($p>0.05$). Thus, H3c and its sub-hypotheses H3c1 and H3c2 were supported.

## 5. Discussions and Theoretical Implications

In this section, the findings will be discussed, and theoretical and managerial implications will be provided. Similar to that of a previous study [50], our findings showed that cognitive trust significantly and positively influences attitudinal participation and actionable participation. However, the findings emphasize that there is no causal relationship between cognitive trusting belief and informational participation. Thus, the cognitive trusting belief of marina users based on the knowledge and competencies of the marina service provider does not influence the tendency of the customer to share more information with the marina.

Our findings significantly confirmed that the emotion-based confidence of marina users led them to exhibit three types of participation behaviors. Affective trust has a positive impact on attitudinal, informational, and actionable participation. In summary, as previous studies also advocated [42,50], by obtaining the trust of their customers, marinas can attain CP in service delivery. For instance, Alves and Mainardes [71] demonstrated that customers' level of trust increases as customers become a part of service delivery more willingly. In the virtual brand community context, Zhihong et al. [72] proposed that customer trust positively affects the knowledge-sharing-related and coproduction-related behaviors of the customers. Schumann et al. [50] empirically demonstrated that cognitive trust directly affects the

***Table 6.*** *GLM results for attitudinal participation and subdimensions of customer cocreated value*

| Parameter | Economic value | | | | Relational value | | | |
|---|---|---|---|---|---|---|---|---|
| | *B* | Std. error | $\chi^2$ | p | *B* | Std. error | $\chi^2$ | p |
| (Intercept) | 5.734 | 0.8688 | 43.560 | 0.000 | 4.277 | 0.8303 | 26.532 | 0.000 |
| **[Experience 1]** (2 years and below) | 0.733 | 0.5055 | 2.102 | 0.147 | 0.643 | 0.4831 | 1.774 | 0.183 |
| **[Experience 2]** (3-5 years) | 0.591 | 0.3160 | 3.495 | 0.062 | 0.089 | 0.3020 | 0.087 | 0.768 |
| **[Experience 3]** (6-8 years) | 0.491 | 0.3145 | 2.437 | 0.119 | 0.214 | 0.3005 | 0.507 | 0.477 |
| **[Experience 4]** (9-11 years) | -0.024 | 0.3141 | 0.006 | 0.940 | -0.010 | 0.3001 | 0.001 | 0.975 |
| **[Experience 5]** (12 years and above) | 0[a] | . | . | . | 0[a] | . | . | . |
| **[Type 1]** (M/Y) | 0.216 | 0.2484 | 0.759 | 0.384 | 0.300 | 0.2374 | 1.598 | 0.206 |
| **[Type 2]** (S/Y) | 0[a] | . | . | . | 0[a] | . | . | . |
| **[Region 1]** (Bodrum) | 0.390 | 0.3149 | 1.536 | 0.215 | 0.200 | 0.3009 | 0.440 | 0.507 |
| **[Region 2]** (Fethiye-Göcek) | 0.219 | 0.3014 | 0.526 | 0.468 | 0.105 | 0.2881 | 0.133 | 0.715 |
| **[Region 3]** (Marmaris) | 0.272 | 0.3149 | 0.746 | 0.388 | -0.050 | 0.3009 | 0.027 | 0.869 |
| **[Region 4]** (Ayvalık) | 0.074 | 0.3948 | 0.035 | 0.851 | -0.151 | 0.3773 | 0.159 | 0.690 |
| **[Region 5]** (İzmir) | 0[a] | . | . | . | 0[a] | . | . | . |
| **CP attitudinal** | **0.414** | **0.0595** | **48.224** | **0.000** | **0.545** | **0.0569** | **91.660** | **0.000** |
| (Scale) | 6.423[b] | 0.3702 | | | 5.866[b] | 0.3381 | | |

Dependent variable(s): CCrt economic value, CCrt relational value
Model: (Intercept), Experience, Position, Type, Region, CP attitudinal
[a]Reference category, [b]Maximum likelihood estimate

***Table 7.*** *GLM results for informational participation and subdimensions of customer cocreated value*

| Parameter | Economic value | | | | Relational value | | | |
|---|---|---|---|---|---|---|---|---|
| | *B* | Std. error | $\chi^2$ | p | *B* | Std. error | $\chi^2$ | p |
| (Intercept) | 9.611 | 0.5486 | 306.897 | 0.000 | 9.389 | 0.5361 | 306.689 | 0.000 |
| **[Experience 1]** (2 years and below) | 0.539 | 0.5212 | 1.069 | 0.301 | 0.388 | 0.5093 | 0.581 | 0.446 |
| **[Experience 2]** (3-5 years) | 0.451 | 0.3233 | 1.947 | 0.163 | -0.095 | 0.3159 | 0.090 | 0.764 |
| **[Experience 3]** (6-8 years) | 0.403 | 0.3234 | 1.553 | 0.213 | 0.098 | 0.3160 | 0.097 | 0.756 |
| **[Experience 4]** (9-11 years) | -0.280 | 0.3198 | 0.767 | 0.381 | -0.347 | 0.3125 | 1.236 | 0.266 |
| **[Experience 5]** (12 years and above) | 0[a] | . | . | . | 0[a] | . | . | . |
| **[Type 1]** (M/Y) | 0.235 | 0.2549 | 0.852 | 0.356 | 0.325 | 0.2491 | 1.701 | 0.192 |
| **[Type 2]** (S/Y) | 0[a] | . | . | . | 0[a] | . | . | . |
| **[Region 1]** (Bodrum) | 0.456 | 0.3229 | 1.991 | 0.158 | 0.286 | 0.3156 | 0.822 | 0.365 |
| **[Region 2]** (Fethiye-Göcek) | 0.368 | 0.3084 | 1.426 | 0.232 | 0.302 | 0.3013 | 1.006 | 0.316 |
| **[Region 3]** (Marmaris) | 0.037 | 0.3215 | 0.013 | 0.908 | -0.359 | 0.3141 | 1.303 | 0.254 |
| **[Region 4]** (Ayvalık) | 0.196 | 0.4047 | 0.235 | 0.628 | 0.011 | 0.3954 | 0.001 | 0.978 |
| **[Region 5]** (İzmir) | 0[a] | . | . | . | 0[a] | . | . | . |
| **CP informational** | **0.164** | **0.0417** | **15.428** | **0.000** | **0.216** | **0.0408** | **27.947** | **0.000** |
| (Scale) | 6.764[b] | 0.3899 | | | 6.459[b] | 0.3723 | | |

Dependent Variable(s): CCrt economic value, CCrt relational value
Model: (Intercept), Experience, Position, Type, Region, CP informational
[a]Reference category, [b]Maximum likelihood estimate

participation behavior of financial service customers. Luk et al. [26] also demonstrated that customer trust in service organizations encourages customers to become a part of service production/delivery processes and that customers also contribute to value creation and efficiency using the service. Moreover, value cocreation can be developed after establishing trust between the parties [73,74].

***Table 8.*** *GLM results for actionable participation and subdimensions of customer cocreated value*

| Parameter | Economic value | | | | Relational value | | | |
|---|---|---|---|---|---|---|---|---|
| | ***B*** | **Std. error** | $\chi^2$ | **p** | ***B*** | **Std. error** | $\chi^2$ | **p** |
| (Intercept) | 4.834 | 0.6844 | 49.893 | 0.000 | 5.395 | 0.6779 | 63.335 | 0.000 |
| **[Experience 1]** (2 years and below) | 0.886 | 0.4831 | 3.363 | 0.067 | 0.792 | 0.4785 | 2.741 | 0.098 |
| **[Experience 2]** (3-5 years) | 0.474 | 0.3007 | 2.484 | 0.115 | -0.093 | 0.2979 | 0.098 | 0.754 |
| **[Experience 3]** (6-8 years) | 0.532 | 0.3004 | 3.137 | 0.077 | 0.252 | 0.2975 | 0.720 | 0.396 |
| **[Experience 4]** (9-11 years) | -0.367 | 0.2978 | 1.518 | 0.218 | -0.436 | 0.2949 | 2.187 | 0.139 |
| **[Experience 5]** (12 years and above) | $0^a$ | . | . | . | $0^a$ | . | . | . |
| **[Type 1]** (M/Y) | 0.125 | 0.2375 | 0.278 | 0.598 | 0.216 | 0.2352 | 0.843 | 0.358 |
| **[Type 2]** (S/Y) | $0^a$ | . | . | . | $0^a$ | . | . | . |
| **[Region 1]** (Bodrum) | 0.543 | 0.3003 | 3.268 | 0.071 | 0.390 | 0.2974 | 1.721 | 0.190 |
| **[Region 2]** (Fethiye-Göcek) | 0.537 | 0.2873 | 3.497 | 0.061 | 0.473 | 0.2846 | 2.757 | 0.097 |
| **[Region 3]** (Marmaris) | 0.094 | 0.2993 | 0.099 | 0.753 | -0.299 | 0.2964 | 1.019 | 0.313 |
| **[Region 4]** (Ayvalık) | -0.043 | 0.3772 | 0.013 | 0.909 | -0.184 | 0.3736 | 0.241 | 0.623 |
| **[Region 5]** (İzmir) | $0^a$ | . | . | . | $0^a$ | . | . | . |
| **CP actionable** | **0.522** | **0.0496** | **110.663** | **0.000** | **0.505** | **0.0492** | **105.702** | **0.000** |
| (Scale) | $5.860^b$ | 0.3378 | | | $5.749^b$ | 0.3314 | | |

Dependent variable(s): CCrt economic value, CCrt relational value
Model: (Intercept), Experience, Position, Type, Region, CP actionable
[a]Reference category, [b]Maximum likelihood estimate

Consistent with other studies [15,71], higher self-efficacy belief encourages customers to undertake more tasks, and their eagerness to be a part of cocreation increases accordingly. Our results confirmed that customer self-efficacy positively and significantly influences each subdimension of CP, i.e., attitudinal, actionable, and informational. This finding is partially contradictory to the results of Chen et al. [41]. They empirically demonstrated that self-efficacy significantly and positively influences attitudinal and actionable participation but does not significantly affect informational participation. Similarly, attitudinal participation was the most affected dimension in their findings. The findings of this research were also consistent with extant literature that propose that marina users with high confidence in their capabilities are more willing to participate in service delivery. Customers with higher self-efficacy beliefs are likely to undertake responsibilities, and their eagerness to participate in cocreation activities increases like other customer types [15,75]. To maintain effective relationships and cocreate values consistent with S-D logic, self-efficacy in service delivery needs to be considered [39,40]. Thus, mutual and interactive relationships between customers and marina organizations can be achieved, and they can cocreate values in service delivery interactions.

This study shows that CP behavior positively influences customer cocreated value. Our research findings indicate a positively significant causal relationship between all types of CP and subdimensions of customer cocreated value as economic and relational values. Attitudinal and actionable participation strongly influence the economic and relational value perceptions of customers, whereas informational participation affects the two value categories relatively less. This outcome is consistent with other findings. Prior studies emphasize the significant and positive influence of CP on the cocreated relational (e.g., [48]) and economic (e.g., [23,47]) values. In the marina service context, the findings showed that marina users do not tend to communicate with other customers or service providers in gathering additional information about service delivery and contributing to the cocreated value. Marina users tend to participate actionably when they think it is required and significantly expected to cocreate economic and relational values. They also behave respectfully and in a friendly manner to the marina staff, and this behavior reveals cocreated economic benefits and relational bonds.

The control variables that were observed to have significant effects on the relationships in the regression analysis are "experience at sea" and "marina region." Furthermore, the regression analysis results indicated that the Marmaris region is important for the relationship between affective trust and attitudinal participation. The same result was observed between cognitive trust and attitudinal participation. The reason for this conclusion is that the Marmaris region has a wide variety of customer profiles and has a more cosmopolitan structure than other regions in Türkiye. Thus, both affective and cognitive trust in this region significantly influence the attitudinal participation of the customer in a positive and significant manner. Furthermore, the group of customers with the least sailing experience (i.e., 2 years or less) significantly influences the way affective trust and informational participation are related. In other words, the emotion-based trust of customers with less experience causes them to participate more informationally. The customers in this group try to obtain more information and experience regarding the marina services. Similarly, the same customer group (i.e., having the least sailing experience) also influences how self-efficacy and informational participation relates to each other. In other words, the perception of self-efficacy of marina users with less sea experience leads them to informational participation.

## 6. Managerial Implications

This study has several implications for marina service providers and marina managers. First, this study defines customer self-efficacy as a significant antecedent for managerial purposes and establishes that customer trust affects different types of CP behaviors. Moreover, consistent with S-D logic, trusting belief is a vital component for creating value jointly. Cocreating value can be achieved only after establishing trust between parties [74]. To establish trust-based relationships, marina firms may consider setting resources aside for training and communication to improve the skills of their employees, such as developing their ability to establish long-term and mutually trusting relationships with customers. Marina management can benefit from the knowledge-sharing culture of the marina industry and obtain essential information as a source of strategic decisions to cocreate value with customers. That is, close contact and social interaction that ensure their participation during service delivery are vital in this industry. Marinas are advised to develop new methods to motivate their customers to participate and be a part of service delivery. As proposed in prior studies [76,77], the higher self-efficacy of customers generally ensures higher technology acceptance. Therefore, digital means of communication can be a useful tool for the marinas to be in regular contact, thereby creating value together with customers during service delivery. Furthermore, big data that can be used to determine customer behavior accumulated through these digital platforms can be managed effectively, and these data can be used in decision-making processes. The management of big data is of great significance for the firm to make strategic decisions to gain a competitive advantage [10]. Social media platforms (e.g., Instagram, Twitter, and Facebook), mobile marketing tools (e.g., mobile applications), and other related technological trends need to be used actively to enhance the participation behavior of customers as it is realized in other types of ports [78]. These satisfactory interpersonal interactions may encourage the customers to participate in service delivery to obtain favorable consequences collaboratively.

## 7. Limitations and Future Research

This study was conducted in the Western Coast Regions of Türkiye, which are the most well-known regions where the most intense yachting activities occur. Future studies should focus on the marina users from the Marmara and Mediterranean regions of Türkiye. In this study, only two customer-related factors and an outcome were involved as antecedents and a result of CP, respectively. Some other factors should also be considered in future research. For instance, culture, which stands out as an antecedent of CP behavior, should be investigated. People from various cultures spend time at marina facilities and exhibit different participation behaviors. As reported by Yi and Gong [46], Koc et al. [79], and Paker and Gok [27], in future studies, the scope of the work can be expanded across borders, and the quantitative data in this study can be compared with future findings abroad. This research has approached CP from a customer-oriented viewpoint. However, other studies have examined the concept from an employee's viewpoint or a dyadic perspective (e.g., [21,80]), and further research may also involve the marina employees' perceptions to provide a similar dyadic perspective. The CP concept has also been analyzed from a positive viewpoint; however, it may sometimes cause value co-destruction (e.g., [81,82]) or employee job stress because of a large amount of work (e.g., [80,83]). Therefore, future research needs to investigate the issue from a negative perspective and evaluate the negative consequences of participation in marina service delivery.

This study was performed on a group of similar people, which caused the data to be less diversified. This study inferred that the non-normal distribution of the data can be attributed to the characteristics of the marina industry. Furthermore, not only did the data fail to meet the multivariate normality requirement but the subdimensions also restrained the emergence of existing relationships. Analyzes were performed with a variance-based structural equation model (i.e., PLS-SEM), which provides flexibility in the assumption of normality. However, on account of several subdimensions of the variables, the reliability and validity values did not exhibit acceptable levels. Thus, the relationships of variables in the model were examined in a binary manner using the GLM although future studies may focus on diverse methods of analysis. In future studies, the mediating role of CP can be examined by determining the antecedent and outcome variables with fewer subdimensions. Furthermore, during survey collection, the number of female participants was increased as much as possible but could not be achieved. In particular, women who spent time in the marina were reluctant to answer the questionnaire. Considering this situation, in future studies, methods to encourage women's participation can be explored.

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Concept design: E. Koç, D.A. Deveci, C. Yıldırım; Data Collection or Processing: E. Koç, C. Yıldırım; Analysis or Interpretation: E. Koç, D.A. Deveci, C. Yıldırım; Literature Review: E. Koç; Writing, Reviewing, and Editing: E. Koç, D.A. Deveci, C. Yıldırım.

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***Appendix 1.*** *Questionnaire items*

| Customer trust |
|---|
| **Cognitive trust** |
| • This marina knows how to provide excellent service. |
| •This marina is competent and has considerable expertise. |
| •The quality of the marina's services is high. |
| •Overall, this marina is experienced. |
| **Affective trust** |
| •The intentions of this marina are benevolent. |
| • This marina pursues predominantly egoistic aims. |
| • This marina acts in my best interest. |
| • This marina aims to help me. |
| **Customer self-efficacy** |
| • I know how to use the services of the marina. |
| • I know how to deal with employees at the marina. |
| • I know what I expect to receive from the marina. |
| **Customer participation** |
| **Attitudinal participation** |
| • I tried to be cooperative with the marina staff. |
| • I am friendly to the marina staff. |
| • I respect the marina staff. |
| Informational participation |
| • I consider other customers' views about the marina. |
| • I spend time searching for information about the marina. |
| • I ask people I know for their opinions about the marina. |
| **Actionable participation** |
| • I intervene when I feel that something is not right when dining in the marina. |
| • I openly discuss questions and concerns with the marina staff. |
| • I ask if I do not know how to obtain service in the marina. |
| **Customer cocreated value** |
| **Economic value** |
| My participation in the service processes helps me to: |
| • Receive higher quality services. |
| • Receive more customized services. |
| • Receive more control over the service quality. |
| **Relational value** |
| My participation in the service processes helps me to: |
| • Build a better relationship with the service provider. |
| • Receive relational approval from the service provider. |
| • Connect better with the service provider. |

***Appendix 2.*** *Normality analysis results of the Kolmogorov-Smirnov test for scales*

| | Mean | Service-dominant | Kolmogorov-Smirnov | p |
|---|---|---|---|---|
| Self-efficacy | 13.57 | 1.75 | 0.246 | 0.000 |
| CT affective | 11.73 | 2.60 | 0.137 | 0.000 |
| CT cognitive | 16.05 | 3.60 | 0.149 | 0.000 |
| CT total | 27.78 | 5.68 | 0.107 | 0.000 |
| CP attitudinal | 13.67 | 1.80 | 0.263 | 0.000 |
| CP informational | 11.54 | 2.58 | 0.127 | 0.000 |
| CP actionable | 12.71 | 2.01 | 0.139 | 0.000 |
| CP total | 37.93 | 4.73 | 0.076 | 0.002 |
| CCrt economic | 11.81 | 2.67 | 0.144 | 0.000 |
| CCrt relational | 12.21 | 2.63 | 0.164 | 0.000 |
| CCrt total | 24.03 | 4.89 | 0.114 | 0.000 |
| CP: Customer participation, CT: Customer trust, CCrt: Customer cocreation | | | | |

***Appendix 3.*** *Reliability analysis results*

| Constructs and items | Scale mean if the item is deleted | Scale variance if the item is deleted | Corrected item-total correlation | Cronbach's alpha | Cronbach's alpha if the item is deleted |
|---|---|---|---|---|---|
| **Customer trust** | | | | **0.908** | |
| **Affective trust** | | | | 0.237 | |
| AFT1 | 9.6395 | 2.990 | 0.392 | | -191[a] |
| AFT2 | 11.7259 | 6.772 | -0.482 | | 0.796 |
| AFT3 | 10.3040 | 2.358 | 0.459 | | -0.423[a] |
| AFT4 | 9.8870 | 2.663 | 0.506 | | -0.386[a] |
| **Cognitive trust** | | | | 0.925 | |
| COGT1 | 12.1561 | 7.327 | 0.819 | | 0.905 |
| COGT2 | 12.0498 | 7.389 | 0.865 | | 0.889 |
| COGT3 | 12.1346 | 7.185 | 0.857 | | 0.891 |
| COGT4 | 11.8140 | 8.039 | 0.763 | | 0.922 |
| **Customer self-efficacy** | | | | **0.762** | |
| SE1 | 9.0781 | 1.523 | 0.558 | | 0.724 |
| SE2 | 9.0000 | 1.454 | 0.667 | | 0.598 |
| SE3 | 9.0581 | 1.609 | 0.561 | | 0.717 |
| **Customer participation** | | | | **0.756** | |
| **Attitudinal participation** | | | | 0.771 | |
| CPAT1 | 9.2625 | 1.429 | 0.544 | | 0.792 |
| CPAT2 | 9.0814 | 1.519 | 0.712 | | 0.574 |
| CPAT3 | 9.0050 | 1.845 | 0.600 | | 0.710 |
| Informational participation | | | | | |

***Appendix 4.*** *Results of the goodness-of-fit indices*

| | Customer trust | Customer participation | Customer cocreated value | Recommended values |
|---|---|---|---|---|
| $\chi^2/df$ | 3.859 | 4.672 | 4.708 | ≤5 |
| **RMSEA** | 0.069 | 0.078 | 0.079 | ≤0.08 |
| **GFI** | 0.977 | 0.960 | 0.980 | ≥0.80 |
| **AGFI** | 0.950 | 0.926 | 0.947 | ≥0.80 |
| **SRMR** | 0.029 | 0.044 | 0.022 | ≤0.10 |
| | $\chi^2$=50.172, *df*=13, p=0.000 | $\chi^2$=112.132, *df*=24, p=0.000 | $\chi^2$=37.665, *df*=8, p=0.000 | |

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# An Application of Fuzzy AHP Using Quadratic Mean Method: Case Study of ENC Preparation Process for Intended Voyages

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## Abstract

Effective management of the electronic nautical charts (ENCs) preparation process using the electronic chart display and information system (ECDIS) is crucial to ensure the safety of ships. Delays or failures in this process can prevent the creation of a safe voyage plan and result in delays or maritime accidents, which may damage a company's reputation. To identify risk factors causing such issues, the quadratic mean method-based Fuzzy Analytical Hierarchy Process was used to weigh and determine the most prominent ones. Additionally, the study proposes specific solutions to eliminate each risk factor. The study's outputs are expected to improve the management of ENC preparation, which is a frequent task for ships using electronic navigation.

**Keywords:** Risk assessment, ECDIS, ENC, Fuzzy analytic hierarchy process, Quadratic mean method

## 1. Introduction

Technological developments have revolutionized navigation, with merchant ships increasingly relying on electronic chart display and information systems (ECDIS) for navigation using electronic nautical charts (ENCs). The ENCs are official navigation charts in digital form, produced by national hydrographic centers [1]. Two types of ENCs are widely used: raster and vector-based [1,2]. Raster navigational charts are digitalized versions of official paper nautical charts [2], whereas electronic navigational charts with vector chart format record digitized data for all charted features needed for safe navigation [3]. The introduction of ECDIS/ENCs on board ships has drastically changed classical navigation practices [4]. Particularly, they are critical in reducing the workload involved in the paper chart-based voyage plan preparation process [4] and improving marine safety [4,5].

Although, earlier, ECDIS/ENC utilization on ships was voluntary [6], now, it has become mandatory navigational equipment under certain conditions [4,6-8]. This obligation has imposed new critical process management responsibilities on ship owners, managers, captains, and navigation officers to ensure marine safety. Among these responsibilities, the ENC preparation process for the intended voyage is a critical process that requires careful management, including obtaining the necessary ENCs, uploading them to the ECDIS, and keeping them updated for safe navigation. Failure in this process may result in operational setbacks that could endanger navigational safety, leading to fatal maritime accidents. Furthermore, failure in the ENC preparation process can cause delays in ship voyages, resulting in economic and reputational losses for companies. Therefore, academic studies aim to identify and eliminate operational errors in this process, enhance marine safety and prevent possible voyage delays.

In this study, we aim to determine potential risk factors that cause delays or failures in the ENC preparation process for the intended voyage and prioritize them using the Fuzzy Analytical Hierarchy Process (FAHP) method with the participation of experts. The study is organized as follows: Section 1 provides concise information on ECDIS/ENC and the transition to paperless navigation on board ships.

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Section 2 summarizes the literature review of ECDIS/ENC. Section 3 introduces the techniques used in this study. Chapter 4 assigns weights to the risk factors identified by experts as causing delays or failures in the ENC preparation process for the intended voyage. Section 5 evaluates the research findings. Section 6 concludes the study and offers recommendations for future studies.

## 2. Literature Review

The literature contains numerous studies on various topics related to ECDIS/ENC. One such topic is ECDIS training. For instance, Brčić et al. [4] surveyed personnel in diverse positions within the maritime transportation sector to develop a new training model for ECDIS and enhance nautical training processes. In another study, Øvergård and Smit [9] examined the effects of participants' sea experience and computer-use skill levels on ECDIS training, using the outputs of ECDIS training courses. Navigation using ECDIS has different characteristics than traditional paper chart-based navigation. In this context, Car et al. [10] classified the potential differences between conventional navigation using paper charts and navigation with ECDIS. Similarly, Weintrit and Stawicki [11] investigated the changes in the bridge work processes for ships navigating using ECDIS. Furthermore, Brčić and Žuškin [12] surveyed officers on the watch to determine the contribution of ECDIS as a primary navigational tool to marine safety and the effects of the gradual shift from conventional navigation to electronic navigation.

The literature contains various studies on integrating ECDIS with other electronic bridge equipment. Koshevyy and Shyshkin [13] proposed updating the existing software used in ECDIS and creating an interface between digital selective calling (DSC) equipment to establish a more efficient structure for navigation and communication. Similarly, Jincan and Maoyan [14] suggested creating a collision avoidance warning system using ECDIS and an automatic identification system (AIS) and tested the proposed model through simulation studies. Tsou [15] proposed a decision support system that uses AIS, ECDIS devices, and a geographic information system module to prevent collision accidents on ships. Improper use of ECDIS has been linked to various maritime accidents [16-19], prompting numerous risk analysis studies. For example, Turna and Öztürk [20] analyzed 22 grounding accidents related to ECDIS/ENC using the 4M Overturned Pyramid model and identified the factors that led to the incidents. Brčić et al. [21] surveyed seafarers in various ranks to determine the importance and necessity of using a secondary positioning resource in ECDIS.

The literature includes various specific studies on ENCs used in ECDIS. For instance, Weintrit [22] has classified existing electronic chart systems by considering factors such as international standards, databases used, and updating methods. Similarly, he compared various electronic chart systems, highlighted differences, and evaluated them in terms of international hydrographic organization (IHO) standards and requirements [23]. In another study, Kang et al. [24] indicated that sounding information in ENCs is obtained from hydrographic surveys and tested the compliance of the data obtained after the soundings with the sounding compilation guideline using the Delaunay triangulation method. Additionally, Palikaris and Mavraeidopoulos [25] recommended selecting the most suitable projections to depict ENCs used in ECDIS and examined the factors that should be considered in the selection process.

Upon examining the studies on ECDIS/ENC in the literature, it is clear that the focus is typically on ECDIS training, comparisons between paperless and paper chart-based navigati various ECDIS integration models, and ENC systems features. In contrast, this study uses the FAHP method to identify the prominent risk factors that cause delays or failures in the ENC preparation process for the intended voyage. Therefore, it distinguishes itself from other literature. Moreover, this study is the first to quantitatively analyze the risk factors encountered during this frequently conducted operational process on ships that navigate with ECDIS. Thus, this study is expected to contribute to the literature and provide valuable insights to designated persons ashore, operational managers, masters, and navigation officers on efficient management of the ENC preparation process for the intended voyages.

## 3. Materials and Methodology

This study includes a comprehensive numerical risk analysis using fuzzy set theory, AHP, and quadratic mean method to assess risk factors encountered during preparation processes for ENCs required for voyages on ships that navigate with ECDIS. This section explains the steps used to apply the methods utilized in the study.

### 3.1. Fuzzy Set Theory

Fuzzy set theory is used in this study to reduce uncertainties that often arise in decision-making processes, providing an effective means to conduct these processes [26]. This theory assigns real numbers between 0 and 1 to represent the membership degrees of each element x in a fuzzy subset, denoted by its membership function $\mu(x)$ [26-28]. Although membership functions can vary significantly in their morphological characteristics and associated fuzzy numbers, triangular and trapezoidal characters are the most commonly used in academic studies [29-32]. Therefore, this study employs triangular fuzzy numbers (TFN). A TFN, denoted by Q = (α, β, Ω), is defined by α and Ω as the lower and upper limit values of Q, respectively, and β as the center value. The membership function of Q, shown as $\mu_Q(x)$:R → [0, 1], can be represented mathematically by the expression in Equation 1 [28,33]:

$$\mu_Q(x)=\begin{cases} 0, & x < \alpha \\ \frac{x-\alpha}{\beta-\alpha'} & \alpha \le x \le \beta \\ \frac{\Omega - x}{\Omega - \beta'} & \beta \le x \le \Omega \\ 0, & x > \Omega \end{cases} \tag{1}$$

Additionally, suppose $Q_1 = (\alpha_1, \beta_1, \Omega_1)$ and $Q_2 = (\alpha_2, \beta_2, \Omega_2)$ are two different TFNs. In this context, Equations 2 and 3 below show the addition and multiplication operations performed with two TFNs, respectively, while Equation 4 shows the reciprocal of a TFN [28, 33]:

$$(\alpha_1, \beta_1, \Omega_1) + (\alpha_2, \beta_2, \Omega_2) = (\alpha_1 + \alpha_2, \beta_1 + \beta_2, \Omega_1 + \Omega_2) \tag{2}$$

$$(\alpha_1, \beta_1, \Omega_1) * (\alpha_2, \beta_2, \Omega_2) = (\alpha_1\alpha_2, \beta_1\beta_2, \Omega_1\Omega_2) \tag{3}$$

$$(\alpha_1, \beta_1, \Omega_1)^{-1} = (1/\Omega_1, 1/\beta_1, 1/\alpha_1) \tag{4}$$

## 3.2. Analytic Hierarchy Process

AHP is an approach developed by Thomas Saaty in 1980 [34] to address multi-criteria problems in a hierarchical order [35]. This hierarchy usually comprises three basic levels; at the top level, there is a target goal; at the level below it, there are the main criteria associated with the established objective; and at the third level, sub-criteria are defined for each of the main criteria [31]. Furthermore, if the study aims to make an optimal choice from predetermined alternatives, these alternatives are placed at the bottom of the hierarchy [36]. This approach involves pairwise comparisons of main and sub-criteria by a designated group of experts [37], resulting in weight values for each evaluated criterion and establishing a priority order based on these values. Due to its significant role in guiding decision-makers, the AHP approach is widely used in various fields [38], such as the maritime industry [36,39].

## 3.3. Integrated Methodology: Fuzzy Analytic Hierarchy Process

The FAHP is a technique that integrates fuzzy set theory and the classical AHP method, which has gained significant use in solving multi-criteria problems. Various FAHP application examples exist in the literature, including the pioneering work of Van Laarhoven and Pedrycz [40], which used triangle fuzzy numbers in pairwise comparisons as one of the first examples of this technique. The technique was further developed by Buckley [41] and Chang [42], with different perspectives on its application. The extent analysis model developed by Chang [42] has gained wide acceptance in the literature due to its simple implementation, adherence to classical AHP steps, and requiring fewer computational processes [43]. However, when weighted with Chang's extent analysis model, some criteria may weigh zero, thus preventing the precise observation of each criterion weight. To address this, Göksu and Güngör [44] introduced the quadratic mean method, which eliminates the possibility of criterion weights being zero and provides an opportunity for more accurate measurements of the determined criteria. This method significantly reduces the computational load in obtaining criterion weights compared to other approaches used in decision-making processes, such as the Technique for Order of Preference by Similarity to Ideal Solution and Vlsekriterijumska Optimizacija I Kompromisno Resenje. In this study, the potential risk factors encountered in ENC preparation processes are weighted by applying FAHP based on the quadratic mean method. Figure 1 illustrates the conceptual framework developed specifically for this study.

In the following section, we will explain the application stages of the method step by step.

### *3.3.1. Implementation phases of the FAHP*

In this section, we will provide a detailed explanation of the implementation phases of FAHP, in order.

Phase 1. Building the hierarchical structure

Initially, the goal of the study, i.e., to identify risk factors that cause delays or failures in ENC preparation processes for the intended voyage, was determined. Next, a hierarchical structure was constructed by defining the main and sub-criteria associated with the identified goal.

Phase 2. Obtaining linguistic assessments for each criterion

The binary comparison matrices were created to determine the superiority of the main criteria and sub-criteria. The linguistic assessments provided by the experts were then converted into corresponding TFNs. Table 1 shows the

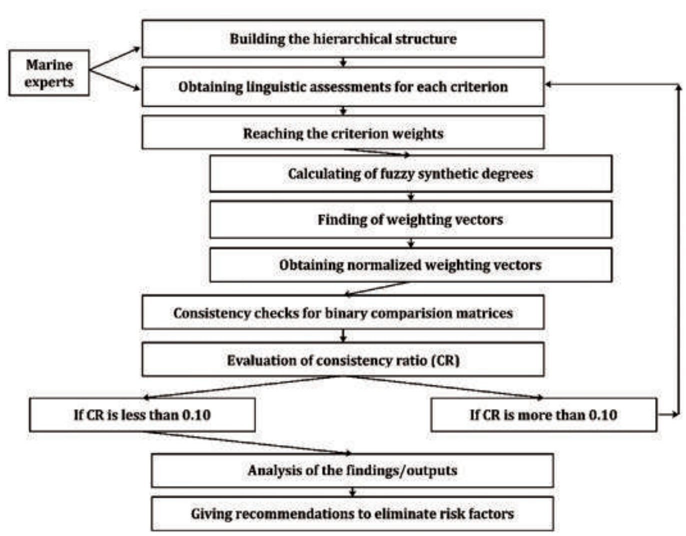


***Figure 1.*** *Conceptual framework designated for the study*

evaluation scale used in the study and the corresponding TFNs for each scale point.

Phase 3. Reaching the criterion weights

***Table 1.*** *Linguistic assessment scale used for the FAHP [45,46]*

| Linguistic evaluation expressions as to the importance level | Equivalent TFNs | Reverses of each TFNs |
|---|---|---|
| Equal (E) | (1,1,1) | (1, 1, 1) |
| Weak (W) | (1,2,3) | (1/3, 1/2, 1) |
| Moderate (M) | (2,3,4) | (1/4, 1/3, 1/2) |
| Moderate plus (MP) | (3,4,5) | (1/5, 1/4, 1/3) |
| Strong (S) | (4,5,6) | (1/6, 1/5, 1/4) |
| Strong plus (SP) | (5,6,7) | (1/7, 1/6, 1/5) |
| Demonstrated (D) | (6,7,8) | (1/8, 1/7, 1/6) |
| Very, very strong (VVS) | (7,8,9) | (1/9, 1/8, 1/7) |
| Extremely (Ex) | (8,9,9) | (1/9, 1/9, 1/8) |

At this stage, a numerical relationship is established between the goal ($g$)and the objects ($X$)$X$ [47]. Assume that there are $n$ sets of objects $X_k$ ($k = 1, 2, 3, 4, \dots, n$) and $m$ sets of goals $g_j$ ($j = 1, 2, 3, 4, \dots, m$) determined [42]. In this approach, it is assumed that each $X$ must achieve a $g$ [42]. Therefore, a total of $m$ extent analysis values are obtained for each X, as shown in Equation 5 .

$$M_{gi}^1, M_{gi}^2, \dots M_{gi}^m,\ i = 1,2,3,4,\dots,n \quad (5)$$

Here, the values denoted by $M_{gi}^j$ $\left(j = 1, 2, 3, 4, \dots, m\right)$ are represented as TFNs. The calculation of fuzzy synthetic degrees for each object is made. These calculation processes are detailed in the following steps [42,43,47]:

1. Calculating fuzzy synthetic degrees

The value of the fuzzy synthetic degrees for object $i$ ($S_i$) is obtained using the following Equation 6:

$$S_i = \sum_{j=1}^{m} M_{gi}^j \times \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1} \quad (6)$$

To calculate the value of $\sum_{j=1}^{m} M_{gi}^j$ in the multiplication above, the fuzzy addition process defined by Equation 7 is utilized.

$$\sum_{j=1=1}^{m} M_{gi}^j = \left(\sum_{j=1=1}^{m} \alpha_j, \sum_{j=1=1}^{m} \beta_j, \sum_{j=1=1}^{m} \Omega_j\right) \quad (7)$$

To obtain the inverse of the second vector $\left[\sum_{i=1=1}^{n}\sum_{j=1=1}^{m} M_{gi}^j\right]$ defined in Equation 6, Equation 8 is utilized.

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^j\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n}\Omega_i}, \frac{1}{\sum_{i=1}^{n}\beta_i}, \frac{1}{\sum_{i=1}^{n}\alpha_i}\right) \quad (8)$$

The synthetic degree values obtained from the TFNs (α, β, Ω) [43] required an approach to estimate the weights of each criterion in the hierarchical structure. The quadratic mean method developed by Göksu and Güngör [44] is utilized in this estimation process to obtain criterion weight vectors. The next step will explain the application steps of the method.

2. Finding of weight vectors ($W'$) sing the quadratic mean method

When determining the criterion weight vectors, as suggested by Chang [42], discovering some criterion weights of zero can create uncertainty in evaluating the criteria. This study employs the quadratic mean method to establish the criterion weight vectors to address this [44]. If there are n TFNs, represented by $M_i = (\alpha_i, \beta_i, \Omega_i)$ (i = 1, 2, 3,..., n.), then the weight vector's n^th^ value can be determined using Equation 9 [44].

$$C(M_n) = \sqrt{\frac{\alpha_n^2 + \beta_n^2 + \Omega_n^2}{3}} \quad (9)$$

The value of the $n^{th}$ TFN in the weight vector is denoted by $C(M\,n)$. Subsequently, each obtained $C(M)$ value is sorted, and a criterion weight vector is created [44, 47]. The mathematical expression for the criterion weight vector is given in Equation 10.

$$W' = \left(C(M_1), C(M_2), \dots, C(M_n)\right)^T \quad (10)$$

3. Obtaining normalized weight vector ($W$)

Normalization is applied to the obtained weight vector ($W'$) resulting in the normalized weight vector ($W$). Each value in this vector represents the priority weight of the corresponding criterion. These values can be used to evaluate the criteria's weights.

#### *3.3.2. Consistency checks for binary comparison matrices*

Defuzzification is used to convert a TFN expressed as M= (x, y, z) to a crisp number. Equation 11, provided below [27], is used for this conversion:

$$Crisp\ (M) = \frac{4y + x + z}{6} \quad (11)$$

The consistency of each pairwise comparison matrices was verified using the consistency check steps suggested by Saaty [48]. To accomplish this, the following equations are used in the order provided below: Equation 12-15 [27,31,48]:

$$E_i = \frac{d_i}{w_i} \quad (12)$$

Criterion weights are represented by $w_i$, while $E_i$ and $d_i$ can be regarded as intermediate values during the calculation process.

$$\lambda_m = \frac{\sum_{i=1}^{n} E_i}{n} \tag{13}$$

$\lambda_m$ represents the largest eigenvalue of the designed matrix, where $n$ denotes the size of the matrix.

$$CI = \frac{\lambda_m - n}{n - 1} \tag{14}$$

Herein, CI represents the consistency index.

$$CR = \frac{CI}{RI} \tag{15}$$

Here, CR denotes the consistency ratio, while *RI* symbolizes the random consistency index. The CR value varies depending on the matrix size, as specified in Table 2. The consistency of the matrices generated from expert evaluations depends on the CR value is less than 10% [27,48].

***Table 2.*** *Random consistency indexes (RI) based on matrix size (n) [49]*

| n value | Equivalent RI | n value | Equivalent RI |
|---|---|---|---|
| 1 | 0.0 | 6 | 1.24 |
| 2 | 0.0 | 7 | 1.32 |
| 3 | 0.58 | 8 | 1.41 |
| 4 | 0.90 | 9 | 1.45 |
| 5 | 1.12 | 10 | 1.49 |

## 4. Quantitative Risk Analysis for the ENC Preparation Process

This study used the FAHP method to identify potential risk factors that could cause delays or failures in the ENC preparation process for the intended voyages. The study successfully identified prominent risk factors.

### 4.1. ENC Preparation Process for the Intended Voyage

Before sailing, the required ENCs for a voyage are determined using specialized software installed on a computer onboard the ship, provided by the ENC service provider. This software includes a digital chart catalog (DCC), which allows the selection of specific ENC cells. A request file is sent via the ship's mail system to the authorized ENC provider, according to company policies and processes, to obtain the chosen ENCs. The communication process may vary based on company policies and procedures. While the communication between the ship and the authorized ENC provider may suffice to obtain the required ENCs, sometimes, the connection between the seafarer, the company, and the approved ENC provider may be necessary. Once the ship's ENC request is approved, the relevant ENC access files, also known as permit files [50], are received via e-mail. The permit files are uploaded and displayed in the ECDIS based on the steps submitted by the authorized ENC chart provider. It is mandatory for ECDIS-equipped ships to use the latest version of relevant ENCs and to keep them up-to-date to meet the chart-carrying requirements stipulated under International Convention for the Safety of Life at Sea (SOLAS) [6,8]. Consequently, the ENCs in the ECDIS and inventory, DCC, and backup devices are updated.

### 4.2. Potential Risk Factors Encountered in ENC Preparation Process for the Intended Voyage

Several risk factors can contribute to failures or delays in preparing ENCs for voyages on ECDIS-equipped ships. Communication-related factors (C) are particularly relevant and must be managed effectively to ensure successful preparation. These factors include a lack of communication between the ship's master and navigation officer (C1), between the ship and ENC provider (C2), between the seafarer and the company (C3), and disconnections in the ship's communication systems (C4).

Furthermore, a lack of knowledge (D) also poses an obstacle to managing this process successfully, which can manifest as a lack of knowledge on the steps required to requisition ENC charts (D1), a lack of knowledge on how to use the DCC (D2), a lack of knowledge on the steps required to upload ENCs to ECDIS (D3), and a lack of information on how to update backup navigation devices (D4).

The software, hardware, and power supplies used in the ENC preparation process for the intended voyage are crucial. The lack of planned maintenance (E) on these components poses a risk to the successful completion of the process. Such hazards or risks include software malfunctions in ECDIS (E1), hardware malfunctions in ECDIS (E2) [50], power supply failures (E3), and emergency power supply failures, including uninterruptible power supplies *(*UPS) (E4).

Procedures (F) are also essential and crucial to avoid undesired delays or failures in the ENC preparation processes. One such risk factor is the lack of procedures (F1). Another is incompatible procedures (F2) that fail to consider the characteristics of the systems used onboard ships. Additionally, complex procedures (F3) and procedures with limited information (F4) are other risk factors that can delay the completion of the process or lead to failure.

### 4.3. Application of the Methodology: FAHP

The study identified potential risk factors by examining various electronic chart usage circulars [50,51] and consulting expert opinions. The identified risk factors that can cause delays or failures in the ENC preparation process for the intended voyage are presented in Table 3.

Furthermore, Figure 2 shows the hierarchical structure constructed for the study.

The study used the perspective of marine experts, who not only assisted in designing the study's hierarchical structure

***Table 3.** Identified risk factors for the ENC preparation process for an intended voyage*

| Abbreviation | Definition |
|---|---|
| GOAL | Risk factors that cause failure/delay in the ENC preparation process for the intended voyage |
| C (Main criteria) | Communication-related risk factors |
| C1 (Sub-criteria) | Lack of communication between the ship's master and the navigation officer |
| C2 (Sub-criteria) | Lack of communication between the ship and ENC provider |
| C3 (Sub-criteria) | Lack of communication between the ship the and company |
| C4 (Sub-criteria) | Disconnections in the ship's communication systems |
| D (Main criteria) | Risk factors due to lack of knowledge |
| D1 (Sub-criteria) | Lack of knowledge of ENC requisition steps |
| D2 (Sub-criteria) | Lack of knowledge on using the digital chart catalog (DCC) |
| D3 (Sub-criteria) | Lack of knowledge on steps to upload ENCs to ECDIS |
| D4 (Sub-criteria) | Lack of knowledge about update steps of backup navigation devices |
| E (Main criteria) | Risk factors related to lack of planned maintenance |
| E1 (Sub-criteria) | Malfunctions occurring in the software of the ECDIS. |
| E2 (Sub-criteria) | Malfunctions occurring in the hardware of the ECDIS. |
| E3 (Sub-criteria) | Power supply failures |
| E4 (Sub-criteria) | Emergency power supply failures, including UPSs |
| F (Main criteria) | Risk factors related to procedures |
| F1 (Sub-criteria) | Lack of procedures |
| F2 (Sub-criteria) | Incompatible procedures |
| F3 (Sub-criteria) | Complex procedures |
| F4 (Sub-criteria) | Procedures with limited information |

but also in evaluating the pairwise comparison matrices developed for both the primary and sub-criteria. Table 4 provides detailed profile information for the seven experts who participated in the study.

The study involved creating five binary comparison matrices that included primary and sub-criteria groups for expert evaluation. To provide their evaluations, experts used the linguistic assessment scale shown in Table 1. Based on the feedback from the experts, these linguistic expressions were converted into equivalent TFNs. Table 5 presents the resulting fuzzy pairwise comparison matrices.

Subsequently, the process of calculating fuzzy synthetic degrees for each criterion began, using Equations (6-8) as per the methodology. Table 6 presents the resulting fuzzy synthetic degrees obtained for each criterion.

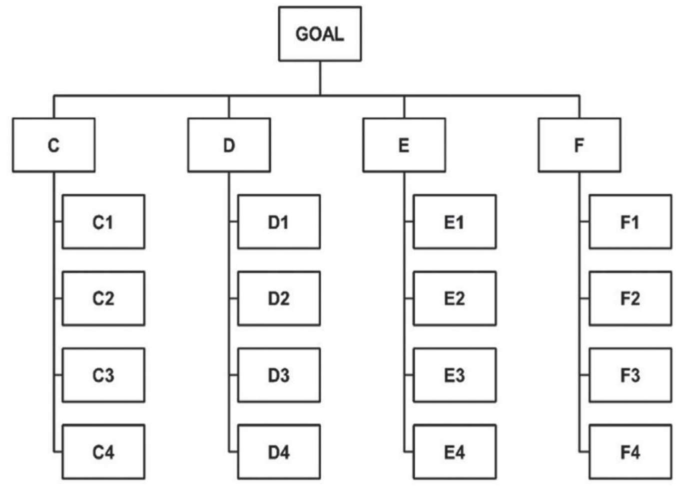


***Figure 2.** Hierarchical structure constructed*

The process of determining weight vectors was initiated by creating the weight values of each criterion using Equation (9). Both primary and sub-criteria weight vectors ($W'$) were obtained through this process. However, these weight vectors could not be used for criterion evaluation. A normalization process was used to determine the priority weight values for each criterion and create normalized weight vectors ($W$). Table 7 presents the obtained weight vectors ($W'$) and normalized weight vectors ($W$).

A consistency test was performed for each paired comparison matrix using Equations (11-15) in sequential order to establish a consistent comparison process and minimize the impact of any potential errors in expert evaluations. Table 8 shows the consistency analysis results obtained for each pairwise comparison matrix.

## 5. Results and Discussion

The consistency tests for all paired comparison matrices designed within the scope of the study resulted in CR values less than 0.10, indicating that the obtained results were consistent [27,48].

The study's analysis of the primary criteria indicated that the most critical risk factor causing delay or failure in the ENC preparation process for the intended voyage was the lack of knowledge (D), with a priority weight of 0.55, followed by communication-related risk factors (C: 0.25), lack of planned maintenance (E: 0.14), and risk factors related to procedures (F: 0.06). As such, specific recommendations as targets to eradicate these risk factors, particularly D and C, are crucial for reducing the risk of delay or failure in this process.

***Table 4.*** *Profile details of the experts*

| Exp. | Professional position | Total sea service (years) | Experiences in navigation with ECDIS/ENC (years) | Competency |
|---|---|---|---|---|
| 1 | Master | 12 | 7 | Oceangoing Master |
| 2 | Master | 11 | 7 | Oceangoing Master |
| 3 | Master | 9 | 6 | Oceangoing Master |
| 4 | Master | 8 | 6 | Oceangoing Master |
| 5 | Navigation Officer | 8 | 5 | Oceangoing Watchkeeping Officer |
| 6 | Navigation Officer | 6 | 5 | Oceangoing Watchkeeping Officer |
| 7 | Navigation Officer | 5 | 5 | Oceangoing Watchkeeping Officer |

***Table 5.*** *Fuzzy binary comparison matrices created within the scope of the study*

| Fuzzy binary comparison matrix for the main criteria | | | | |
|---|---|---|---|---|
| | **C** | **D** | **E** | **F** |
| **C** | 1.00-1.00-1.00 | 0.23-0.31-0.44 | 1.33-2.38-3.44 | 2.38-3.45-4.35 |
| **D** | 2.27-3.22-4.35 | 1.00-1.00-1.00 | 4.35-5.26-6.25 | 6.25-7.14-8.33 |
| **E** | 0.29-0.42-0.75 | 0.16-0.19-0.23 | 1.00-1.00-1.00 | 1.33-2.38-3.45 |
| **F** | 0.23-0.29-0.42 | 0.12-0.14-0.16 | 0.29-0.42-0.75 | 1.00-1.00-1.00 |
| **Fuzzy binary comparison matrix for sub-criteria of communication-related risk factors** | | | | |
| | **C1** | **C2** | **C3** | **C4** |
| **C1** | 1.00-1.00-1.00 | 0.31-0.44-0.82 | 0.14-0.16-0.19 | 1.22-2.22-3.22 |
| **C2** | 1.22-2.27-3.22 | 1.00-1.00-1.00 | 0.23-0.31-0.44 | 3.45-4.54-5.55 |
| **C3** | 5.26-6.25-7.14 | 2.27-3.22-4.35 | 1.00-1.00-1.00 | 7.69-8.33-9.00 |
| **C4** | 0.31-0.45-0.82 | 0.18-0.22-0.29 | 0.11-0.12-0.13 | 1.00-1.00-1.00 |
| **Fuzzy binary comparison matrix for sub-criteria of risk factors due to lack of knowledge** | | | | |
| | **D1** | **D2** | **D3** | **D4** |
| **D1** | 1.00-1.00-1.00 | 2.00-3.00-4.00 | 4.76-5.88-6.66 | 7.69-8.33-9.00 |
| **D2** | 0.25-0.33-0.50 | 1.00-1.00-1.00 | 1.22-2.22-3.22 | 2.56-3.57-4.54 |
| **D3** | 0.15-0.17-0.21 | 0.31-0.45-0.82 | 1.00-1.00-1.00 | 1.33-2.38-3.45 |
| **D4** | 0.11-0.12-0.13 | 0.22-0.28-0.39 | 0.29-0.42-0.75 | 1.00-1.00-1.00 |
| **Fuzzy binary comparison matrix for sub-criteria of risk factors related to lack of planned maintenance** | | | | |
| | **E1** | **E2** | **E3** | **E4** |
| **E1** | 1.00-1.00-1.00 | 1.43-2.49-3.57 | 5.26-6.25-7.14 | 7.69-8.33-8.95 |
| **E2** | 0.28-0.40-0.70 | 1.00-1.00-1.00 | 1.89-2.94-4.02 | 4.16-5.26-6.25 |
| **E3** | 0.14-0.16-0.19 | 0.25-0.34-0.53 | 1.00-1.00-1.00 | 1.33-2.38-3.45 |
| **E4** | 0.11-0.12-0.13 | 0.16-0.19-0.24 | 0.29-0.42-0.75 | 1.00-1.00-1.00 |
| **Fuzzy binary comparison matrix for sub-criteria of risk factors related to procedures** | | | | |
| | **F1** | **F2** | **F3** | **F4** |
| **F1** | 1.00-1.00-1.00 | 0.31-0.44-0.82 | 0.12-0.13-0.15 | 0.14-0.17-0.20 |
| **F2** | 1.22-2.27-3.22 | 1.00-1.00-1.00 | 0.20-0.24-0.32 | 0.24-0.32-0.49 |
| **F3** | 6.67-7.69-8.33 | 3.12-4.17-5.00 | 1.00-1.00-1.00 | 1.10-2.13-3.12 |
| **F4** | 5.00-5.88-7.14 | 2.04-3.12-4.17 | 0.32-0.47-0.91 | 1.00-1.00-1.00 |

Among the communication-related risk factors (C) sub-criteria, the lack of communication between the ship and the company (C3) had the highest priority weight of 0.56, making it the most significant risk factor leading to delays or failures in the ENC preparation processes, followed by the lack of communication between the ship and the

ENC provider (C2: 0.25), lack of communication between the ship's master and navigation officer (C1: 0.13), and disconnections in the ship's communication systems (C4: 0.05). Effective communication must be established among all parties responsible, ensuring timely receipt and proper display of required ENCs on the ECDIS to prevent delays or failures in the ENC preparation process. A clear definition of responsibilities for all involved parties is essential to achieve this. Given the importance of communication technologies in ship operations [52], ship communication systems must function efficiently. The computers with e-mail systems, critical for ship communication, should be supported by UPSs to prevent disruption from potential power failures. Furthermore, to prevent computer viruses and cyber-attacks, antivirus software should be installed to protect the e-mail and internet systems onboard.

***Table 6.*** *Calculated fuzzy synthetic degrees ($S_i$)*

| Fuzzy synthetic degrees calculated for the main criteria | |
|---|---|
| $S_C$ | 0.13-0.24-0.40 |
| $S_D$ | 0.37-0.56-0.86 |
| $S_E$ | 0.07-0.13-0.23 |
| $S_F$ | 0.04-0.06-0.10 |
| **Fuzzy synthetic degrees calculated for the sub-criteria of C** | |
| $S_{C1}$ | 0.07-0.12-0.20 |
| $S_{C2}$ | 0.15-0.25-0.39 |
| $S_{C3}$ | 0.41-0.58-0.81 |
| $S_{C4}$ | 0.04-0.05-0.08 |
| **Fuzzy synthetic degrees calculated for the sub-criteria of D** | |
| $S_{D1}$ | 0.41-0.58-0.83 |
| $S_{D2}$ | 0.13-0.23-0.37 |
| $S_{D3}$ | 0.07-0.13-0.22 |
| $S_{D4}$ | 0.04-0.06-0.09 |
| **Fuzzy synthetic degrees calculated for the sub-criteria of E** | |
| $S_{E1}$ | 0.38-0.54-0.76 |
| $S_{E2}$ | 0.18-0.29-0.44 |
| $S_{E3}$ | 0.07-0.12-0.19 |
| $S_{E4}$ | 0.04-0.05-0.08 |
| **Fuzzy synthetic degrees calculated for the sub-criteria of F** | |
| $S_{F1}$ | 0.04-0.06-0.09 |
| $S_{F2}$ | 0.07-0.12-0.20 |
| $S_{F3}$ | 0.31-0.48-0.71 |
| $S_{F4}$ | 0.22-0.34-0.54 |

***Table 7.*** *The calculated weight vectors (W′) normalized weight vectors (W)*

| Designed Matrices | (W′) | (W) |
|---|---|---|
| C, D, E, F | $W' = (0.28,0.63,0.16,0.07)^T$ | $W = (0.25,0.55,0.14,0.06)^T$ |
| C1, C2, C3, C4 | $W' = (0.14,0.28,0.62,0.06)^T$ | $W = (0.13,0.25,0.56,0.05)^T$ |
| D1, D2, D3, D4 | $W' = (0.63,0.26,0.15,0.07)^T$ | $W = (0.57,0.23,0.14,0.06)^T$ |
| E1, E2, E3, E4 | $W' = (0.58,0.32,0.13,0.06)^T$ | $W = (0.53,0.29,0.12,0.06)^T$ |
| F1, F2, F3, F4 | $W' = (0.07,0.14,0.53,0.39)^T$ | $W = (0.06,0.12,0.47,0.35)^T$ |

Among the risk factors resulting from the lack of knowledge (D), the risk factor with the most significant negative impact on the process was the lack of knowledge about the steps for ENC requisition (D1), with a priority weight of 0.57. The lack of knowledge about using the DCC (D2) was identified as the second most critical risk factor, with a priority weight of 0.23. These risk factors were followed by the lack of knowledge about procedures for uploading ENCs to ECDIS (D3: 0.14) and the lack of knowledge about the update steps of backup navigation devices (D4: 0.06). To mitigate these risks, the officer in charge of the navigational planning and the ship's master should receive computer-aided simulation training on the ENC preparation process before joining the seafarer. This training should consider the specific characteristics of the ECDIS and ENCs used onboard ships [10,53,54]. Additionally, to ensure the effective use and maintenance of ECDIS/ENCs on ships, it is recommended to increase the frequency of internal audits [55]. Furthermore, detailed information on this issue should also be shared during the duty handover onboard.

Another significant criterion that negatively affects the ENC preparation process is the risk factors arising from the lack of planned maintenance (E). Among these factors, malfunctions in the ECDIS software (E1) were identified as the most significant, with a priority weight of 0.53, causing delays or failures in the ENC preparation process.

***Table 8.*** *The obtained consistency analysis results*

| Designed matrices | $\lambda_m$ | CI | RI | CR |
|---|---|---|---|---|
| C, D, E, F | 4.10867 | 0.03622 | 0.90 | 0.04 |
| C1, C2, C3, C4 | 4.08999 | 0.02999 | 0.90 | 0.03 |
| D1, D2, D3, D4 | 4.08306 | 0.02768 | 0.90 | 0.03 |
| E1, E2, E3, E4 | 4.08850 | 0.02950 | 0.90 | 0.03 |
| F1, F2, F3, F4 | 4.09111 | 0.03037 | 0.90 | 0.03 |

Other critical risk factors in order of importance are malfunctions occurring in the hardware of the ECDIS (E2: 0.29), power supply failures (E3: 0.12), and emergency power supply failures, including UPSs (E4: 0.06). Thus, it is essential to establish a planned maintenance system for the software, hardware, and power sources involved in the ENC preparation process to mitigate these risk factors. This system should include regular updates of the ECDIS software by the manufacturer's instructions and routine checks on other hardware components such as fans, monitors, universal serial bus (USB) slots, and keyboards to prevent any deformation. Furthermore, it is crucial to integrate an adequate power supply as specified by the ECDIS, International Maritime Organization (IMO), and flag state; also, it is vital to replace UPS batteries before they reach their expiration date to ensure optimal performance [56]. To ensure compliance with these requirements onboard ships, ports, and flag state officers should conduct frequent audits.

The analysis of sub-criteria related to procedures (F) identified complex procedures (F3) as the primary risk factor with a priority weight of 0.47 that can disrupt the process. The other risk factors in the order of priority were procedures with limited information (F4: 0.35), incompatible procedures (F2: 0.12), and lack of procedures (F1: 0.06) that could cause delays or errors in the ENC preparation process for the intended voyage. To address these issues, the procedures created for this process should be easy to understand and apply, tailored to the unique characteristics of the systems used on the ships. A team with specialized knowledge and experience about the ECDIS installed on a seafarer should be established. If this is not feasible in the short term, assistance from an independent organization should be sought [57]. Furthermore, the prepared procedures should provide detailed instructions for handling emergencies such as ECDIS signal loss or ENC scale failure [20].

## 6. Conclusion

The study examined risk factors that can cause delays or failures in preparing ENC for planned voyages. A FAHP application based on the quadratic mean method, a novel criterion weighting approach [44], was used to identify prominent risk factors. The results indicated that the most significant risk factors hindering the successful management of the process are those arising from a lack of knowledge (D) and communication-related risks (C). Other identified risk factors were the lack of planned maintenance (E) and procedure-related risks (F) based on their priority weights. Consequently, the study emphasizes the necessity of regulatory and preventive measures such as training, effective communication, technological infrastructure development, and the publication of appropriate procedures to eliminate these risk factors. The study's findings increase seafarers' awareness of the risk factors that disrupt the operational process frequently performed on ECDIS-equipped ships. Further research exploring the effect of human factors on inappropriate ECDIS use could add value to the literature.

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### Authorship Contributions

Concept design: A.L. Tunçel, Ö. Arslan, E. Akyüz, Data Collection or Processing: A.L. Tunçel, Analysis or Interpretation: A.L. Tunçel, Ö. Arslan, Literature Review: A.L. Tunçel, Ö. Arslan, E. Akyüz, Writing, Reviewing and Editing: A.L. Tunçel, Ö. Arslan, E. Akyüz,

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