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Remzi FIŞKIN

Ordu University Faculty of Marine Sciences, Department of Marine Transportation Engineering, Ordu, Türkiye

Dear Colleagues and Researchers,

We are leaving one more year behind with the last issue of JEMS. 2022 has been an effective year for JEMS. Together with the last issue, we are proud to have published a total of 23 original articles from different nationalities and disciplines. JEMS, currently indexed in databases such as ESCI, TRDizin, EBSCO, continues its development with this indexing. Our efforts are to be increasingly continued in 2023 to have JEMS accepted by SCI-E. Increasing interest in JEMS is motivating the editorial board's efforts to move the journal forward.

Moreover, our intensive efforts have reduced the article evaluation period to 2 months. We aim to continue to provide at least this period next year. There are reviewers from different nationalities and disciplines in the reviewer pool. We aim to continue to expand the reviewer pool in 2023. The increasing number of articles needs multiple evaluation by a reviewer. I would like to give very special thanks to the academics who accepted to be reviewers and assessed the articles. Lastly, congratulations and many thanks to all our authors whose articles were published in 2022 and to our esteemed sponsors.

On the other hand, I wish editor-in-chief Prof. Dr. Selçuk NAS, who had health problems and had a surgical operation, get well soon. I hope he will return to his post at the journal by the end of January.

As I end our words with these feelings, I wish everyone a healthy, happy, peaceful, and successful year. I hope that it will be a year full of collaboration and science.

Best Regards,

On behalf of the Editorial Board

Dr. Remzi FIŞKIN

Deputy Editor

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A Comprehensive Risk Assessment Analysis of Accidental Falls in Shipyards Using the Gaussian Fuzzy AHP Model

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Abstract

Falling from a height is the major cause of death and injuries in shipyards and similar constructive industries. This study aims to comprehensively investigate the causes of occupational accidental falls in shipyards. A solution methodology is presented to determine the weights of these causes of accidental falls. In this solution methodology, weighting scores are assigned to experts according to their professional position, work experience, and education level. Moreover, consistency analysis is performed for expert judgments and their aggregated forms. Although the findings show that the dominant cause of accidental falls in shipyards is human risks, the shipyard area and environmental risks, organizational risks, and safety risks should also be considered as a whole.

Keywords: Falling from a height, Shipyard risk analysis, Fuzzy AHP, Gaussian AHP

1. Introduction

Shipbuilding is a complex engineering application that considers customer expectations and includes many activities, such as production, construction, and testing. A ship basically needs naval architecture and marine engineering applications to navigate safely by providing the desired hydrostatic and hydrodynamic features on the water surface. Moreover, different implementation areas, such as materials, electronics, rubber-plastic, and paint, are also performed during ship production. Therefore, shipyards produce according to a multidisciplinary production philosophy [1].

As a result of the multidisciplinary production philosophy in shipyards, many workers from different firms work simultaneously in the shipyard environment. Many of these firms are called subcontractors. Subcontractors perform various tasks through their workers during the ship production process. The shipyard also has its own workers in addition to subcontractors. Thus, many workers performing various jobs must work together in the shipyard environment at the same time. Considering the limited shipyard area, this situation causes integration and organization problems in the shipyard's general working plan [2]. In addition to these ship production activities, shipyards perform maintenance and repair occupations. All these activities have a completion time, which increases the difficulty of integration and organization problems in the shipyard's general working plan.

Occupational accidents occur as a result of the integration and organization problems in the shipyard's general plan. Typically, occupational accidents in shipyards occur where human and machine factors are dominant. Considering that many employees work using different machines and equipment in the shipyard environment, occupational accidents become inevitable. Therefore, shipyards aim to minimize occupational accidents by taking many precautions. Moreover, many researchers have conducted academic studies on occupational accidents in shipyards that result in death, injury, and large financial losses (for the accident victims, shipyard, and governmental institutions).

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Various occupational accidents occur in shipyards for different reasons. Barlas [3] investigated the causes of 115 fatal occupational accidents at shipyards in Türkiye between 2000-2010 and ranked the results as follows: falling from a height (39.1%), exposure to electric shock (15.7%), fire and/or explosion (15.7%), being struck by or struck against objects (12.1%), caught in between (squeeze) (7.8%), and other causes (9.6%). Barlas and Izci [2] queried the causes of occupational accidents that resulted in the death of 126 workers in shipyards in Türkiye between 2004-2014 and obtained the following findings: falling from a height (30.2%), struck by/struck against objects, caught in between (23%), fire and/or explosion (16.7%), exposure to electric shock (13.5%), drowning (11.1%), and other causes (5.6%). These two studies obviously show that the primary cause of fatal occupational accidents in shipyards is falling from a height. This finding indicates the focus of our study.

Very few studies are available in the literature that involves the causes of accidental falls in shipyards. The existing studies, on the other hand, do not directly address this issue, and their horizon on the topic is limited. Barlas [4] defined five criteria and five precautions for the causes of fatal accidental falls in shipyards in the Tuzla region of Türkiye from 2000 to 2011 and ranked these criteria using the analytic hierarchy process (AHP) method. In this study, the best precaution against accidental falls was wearing and checking parachute-type safety belts. Seker et al. [5] calculated the occurrence probability of critical risk criteria in shipyards using an integrated approach and concluded that falls from height were one of the top three occupational accidents at a shipyard. Except for these two papers, studies have addressed the general causes of occupational accidents and risk assessment analyses in shipyards.

To the best of our knowledge, the causes of accidental falls in shipyards have not been comprehensively studied in the literature. This study aims to fill this gap in the literature. The key contributions of our study are as follows:

(i) Accidental falls, which are the major cause of occupational fatalities in shipyards, have been extensively investigated for the first time.

(ii) A solution methodology is presented to calculate the weighting of the main criteria and sub-criteria that cause accidental falls in shipyards.

Eventually, four main criteria and 28 sub-criteria that cause falls accident are determined for this paper. Then, the main criteria and sub-criteria are ranked according to their level of importance using the proposed solution methodology.

The remainder of this paper is organized as follows: A comprehensive literature review on occupational fatalities and accidents in shipyards is presented in Section 2. The design of a solution methodology of the problem is provided in Section 3. Section 4 addresses a detailed application to the causes of falls in shipyards. Computational results and discussions are given in Section 5. Section 6 concludes this paper and gives its limitations and the research directions they entail.

2. Literature Review

This section reviews the academic literature regarding occupational accidents and their variants. Many researchers have conducted many studies considering the complex business and planning processes, human factors, and organizational and safety factors in shipyards. Saarela [6] performed a two-phase campaign with workers regarding accidents in shipyards and compared results before and after the campaign. The respondents gave more specific answers to the survey questions after the campaign. Celebi et al. [7] conducted a study examining accidents and diseases in Turkish shipyards in particular years. They investigated the effects of paint and welding and surface preparation operations on human health and bodily injuries and the causes of occupational accidents. Basuki et al. [8] performed a probabilistic risk analysis suitable for the shipyard industry by establishing a material network model through the Bayesian method. Ozkok [9] conducted a risk assessment of the riskiest activities and workstations in the hull production process of a ship using the failure mode and effects analysis method. Yilmaz et al. [10] analyzed the accidents that occurred in shipyards in the Tuzla İstanbul region using the shipyard accidents analysis and management system module. Ozkok [11] applied a risk evaluation with the fuzzy AHP (FAHP) method to the hazards that occurred in the pin jig work unit of shipyards. Acuner and Cebi [12] proposed an effective risk prevention model based on fuzzy set theory to minimize work accidents in shipyards. Zaman et al. [13] aimed to reduce occupational accidents in shipyards by determining the relationship between individual characters and occupational accidents using bivariate analysis. Wulandari et al. [14] conducted a risk assessment analysis during the painting process of a ship's hull and offered suggestions to decrease these risks. Moreover, in academic studies, specific papers are available on topics such as occupational exposure, illness, and health in shipyards [15-21].

The above papers reveal the shortcomings of a comprehensive study of the causes of falls from height, which is the primary cause of fatal accidents in shipyards. This study focuses on filling the current gap in the literature.

3. Materials and Methods

3.1. Design of the Solution Methodology

In this study, a solution methodology is presented to make a plausible analysis of accidental falls in shipyards. According to this solution methodology, evaluation criteria are determined first. The next step includes two straightforward processes: the expert weighting process and the expert consistency process. While the expert weighting process determines weighting scores for each expert, the expert consistency process guarantees that the individual and aggregated judgments are consistent. Finally, data analysis is performed with the Gaussian AHP method, and the evaluation criteria are ranked considering their importance levels. The stages of the solution methodology are shown in Figure 1.

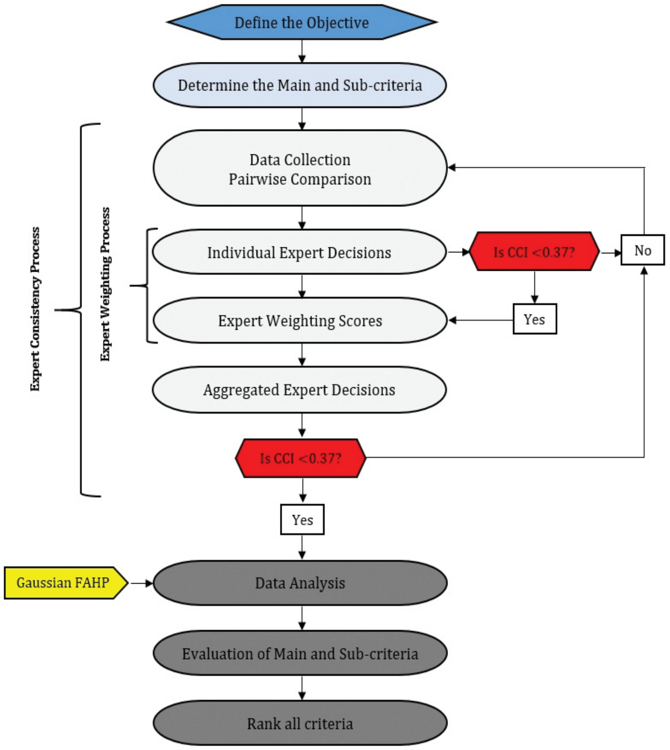

Figure 1. *Solution methodology for the study*

3.2. Determining the Evaluation Criteria

First, the evaluation criteria must be determined to analyze the causes of accidental falls in shipyards. No specific method or technique is available to determine these evaluation criteria. When the process of determining the evaluation criteria in the literature is examined, the accident reports from the shipyard environment and the experiences of practitioners are considered. However, the evaluation criteria in the literature for accidental falls differ from study to study. This study intends to collect these scattered evaluation criteria under certain main titles and turn them into a holistic form. Consequently, a comprehensive dataset on the evaluation criteria is composed considering the studies in the literature review (Section 2). Moreover, since the shipbuilding industry shows some similarities with the construction industry [2], studies regarding accidental falls in the construction industry [22-28] are also considered.

3.3. Data Collection

The data collection step must be carried out carefully for a reasonable data analysis. In this study, an online e-questionnaire that includes six chapters is prepared via Google Forms for experts to compare the main criteria and sub-criteria pairwise (linguistic comparison). In the first chapter, the experts provide information such as their name, educational status, professional position, and work experience. In the second chapter, the main criteria are defined in detail, and then the experts compare these criteria pairwise. In the third and remaining chapters, the experts pairwise compare the sub-criteria of the main criteria. This online e-questionnaire was delivered to experts working in the shipbuilding sector, six of whom filled out the forms. In this way, the data collection process is completed.

3.4. Expert Consistency Process

The expert consistency process guarantees the consistency of the individual and aggregated judgments obtained with the data collection. Saaty and Vargas [29] stated that all expert judgment should be consistent to make a correct evaluation process and used the consistency ratio formulation. Many proposed consistency calculation approaches are found in the literature. Crawford and Williams [30] presented the row geometric mean method (RGMM) for consistency of judgment matrices. Aguarón and Moreno-Jiménez [31] used the geometric consistency index (*GCI*) for the expert decision matrix. In the *GCI* approach, the threshold values of the judgment matrix are determined as $\overline{\text{GCI}} = 0.31$, $\overline{\text{GCI}} = 0.35$, and $\overline{\text{GCI}} = 0.37$ for $n = 3$, $n = 4$, and $n > 4$, respectively. In this study, the centric consistency index (*CCI*) formulation proposed by Bulut et al. [32] is performed for the consistency of the decision matrix. Since the *CCI* is a fuzzy extended type of *GCI*, threshold values are equal. The *CCI* formulation is as follows:

$$\mathrm{CCI}(A) = \frac{2}{(n-1)(n-2)} \sum_{i<j} \left(\log\left(\frac{a_{Lij} + a_{Mij} + a_{Uij}}{3}\right) - \log\left(\frac{w_{Lij} + w_{Mij} + w_{Uij}}{3}\right) + \log\left(\frac{w_{Lj} + w_{Mj} + w_{Uj}}{3}\right)\right)^2 \quad (1)$$

In Equation 1, A is a fuzzy decision matrix, and w is a priority vector derived from using the RGMM. If $CCI(A) = 0$, then A is completely consistent. A is sufficiently consistent when $CCI(A) < \overline{GCI}$.

3.5. Expert Weighting Process

In the fuzzy logic environment where linguistic terms are used, the evaluation criteria (main and sub-criteria) should be compared pairwise by experts. Because experts have different professions, educational statuses, and experience in the shipbuilding industry, they do not make these pairwise comparisons from the same perspective. In this study, weighting scores are calculated by considering the education level, professional position, and work experience of each expert. By doing so, each expert influences the aggregated decision matrices as much as their weighting score.

3.6. Gaussian Fuzzy AHP

The aggregated decision matrices obtained via expert consistency and the expert weighting process should be analyzed. Many methods, such as the AHP [33], FAHP [34], fuzzy hierarchical analysis [35], and synthetic extent analysis method [36], have been proposed in the literature to perform these analyses. These methods model and numerically analyze people's linguistic terms using fuzzy set theory [37]. However, no rule or equation governs which method should be preferred [38]. Among these methods, researchers have mostly applied Chang's method recently. Although Chang's method is frequently preferred in the literature, its use presents problems [39]. In this method, two triangular fuzzy numbers may not intersect, and one or more criteria weights may equal zero as a result of calculations. To overcome this shortcoming, Hefny et al. [40] proposed using Gaussian fuzzy numbers. Gaussian fuzzy numbers provide an exact intersection point between all fuzzy numbers. Thus, the criteria are prevented from having equal rank and evaluation [39,40]. In this study, there are four main criteria, comprising a total of 28 sub-criteria, and a unique ranking must be made for an accurate evaluation. This fact is the most important justification for choosing the Gaussian fuzzy AHP method in this study.

The Gaussian function needs only two parameters, μ (center) and σ (width), as presented in Figure 2. Figure 3 shows the intersection of two Gaussian functions. The Gaussian function is defined as follows:

$$Gaussian(x: \mu, \sigma) = exp\left[\frac{-(x-\mu)}{2\sigma^2}\right] \tag{2}$$

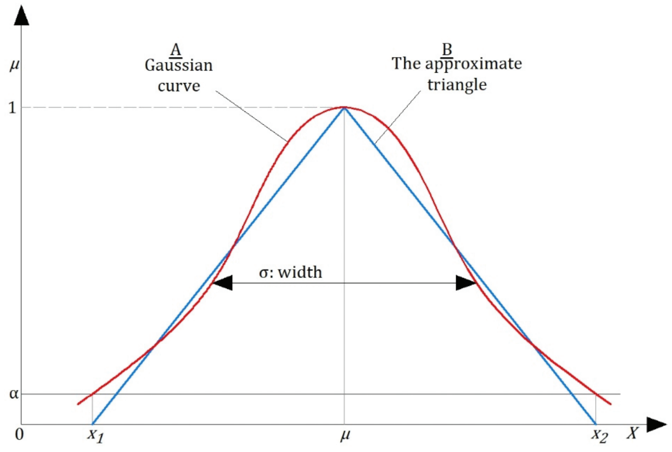

Figure 2. *Gaussian (A) and the approximate triangle (B) curves*

With the intersection of two Gaussian functions as in Figure 3, any α level is calculated as follows:

$$\alpha = \exp\left[\frac{-(x-\mu)}{2\sigma^2}\right] \tag{3}$$

$$x_1 = \mu - \sigma\sqrt{-Ln(\alpha)} \tag{4}$$

$$x_2 = \mu + \sigma\sqrt{-Ln(\alpha)} \tag{5}$$

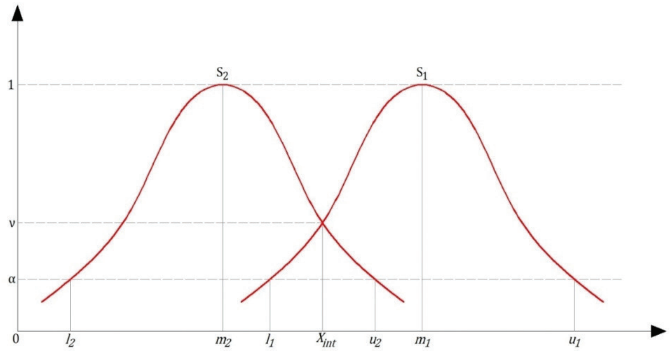

Figure 3. *Intersection of two Gaussian functions*

Assuming that G_{ij} is the preference matrix, then:

$$S_i = \frac{\sum_j G_{ij}}{\sum_i \sum_j G_{ij}} = \frac{\sum_j (l_i^j, m_i^j, u_i^j)}{\sum_i \sum_j (l_i^j, m_i^j, u_i^j)} \tag{6}$$

where $l_i^j \cong m_i^j - \sigma_i^j\sqrt{-Ln(\alpha)}$ and $u_i^j \cong m_i^j + \sigma_i^j\sqrt{-Ln(\alpha)}$.

For the triangular approximation, $\alpha = 0.001$. Then, the following steps are applied:

Step 1:

$$S_i = \frac{\left(\sum_j l_i^j, \sum_j m_i^j, \sum_j u_i^j\right)}{\left(\sum_i \sum_j l_i^j, \sum_i \sum_j m_i^j, \sum_i \sum_j u_i^j\right)} = \left(\frac{\sum_j l_i^j}{\sum_i \sum_j u_i^j}, \frac{\sum_j m_i^j}{\sum_i \sum_j m_i^j}, \frac{\sum_j u_i^j}{\sum_i \sum_j l_i^j}\right) \tag{7}$$

$$\sum_j l_i^j = \sum_j m_i^j - \sum_j \sigma_i^j \left(\sqrt{-Ln(\alpha)}\right) \tag{8}$$

$$\sum_j u_i^j = \sum_j m_i^j + \sum_j \sigma_i^j \left(\sqrt{-Ln(\alpha)}\right) \tag{9}$$

$$\sum_i \sum_j l_i^j = \sum_i \sum_j m_i^j - \sum_i \sum_j \sigma_i^j \left(\sqrt{-Ln(\alpha)}\right) \tag{10}$$

$$\sum_i \sum_j u_i^j = \sum_i \sum_j m_i^j + \sum_i \sum_j \sigma_i^j \left(\sqrt{-Ln(\alpha)}\right) \tag{11}$$

$$S_i = \left(x_{S_i}^L, m_{S_i}, x_{S_i}^R\right) \tag{12}$$

where $m_{S_i} = \frac{\sum_j m_i^j}{\sum_i \sum_j m_i^j}$, $x_{S_i}^L = \frac{\sum_j l_i^j}{\sum_i \sum_j u_i^j}$ and $x_{S_i}^R = \frac{\sum_j u_i^j}{\sum_i \sum_j l_i^j}$

After the above formulation processes, S_i must be converted back to an asymmetric Gaussian fuzzy number as follows:

$$\sigma_{S_i}^L = \frac{m_{S_i} - x_{S_i}^L}{\sqrt{-Ln(\alpha)}} \tag{13}$$

$$\sigma_{S_i}^L = \frac{m_{S_i} - x_{S_i}^L}{\sqrt{-Ln(\alpha)}} \tag{14}$$

where $\sigma_{S_i}^L$ and $\sigma_{S_i}^R$ are the width of the left and right branches of the Gaussian fuzzy number, respectively.

After Step 1, the membership function for asymmetric Gaussian numbers is as follows:

$$\mu_{S_i}(x) = \begin{cases} exp\left[-\left(\frac{x - m_{S_i}}{\sigma_{S_i}^L}\right)^2\right], & if\ x \le m_{S_i} \\ exp\left[-\left(\frac{x - m_{S_i}}{\sigma_{S_i}^R}\right)^2\right], & if\ x > m_{S_i} \end{cases} \tag{15}$$

Step 2: Assume that $\mu_1(x)$ and $\mu_2(x)$ are two Gaussian numbers. $\mu_1(x)$ and $\mu_2(x)$ are defined as follows:

$$\mu_1(x) = \begin{cases} exp\left[-\left(\frac{x - m_{S_1}}{\sigma_{S_1}^L}\right)^2\right], & if\ x \le m_{S_1} \\ exp\left[-\left(\frac{x - m_{S_2}}{\sigma_{S_2}^R}\right)^2\right], & if\ x > m_{S_2} \end{cases} \tag{16}$$

and

$$\mu_2(x) = \begin{cases} exp\left[-\left(\frac{x - m_{S_2}}{\sigma_{S_2}^L}\right)^2\right], & if\ x \le m_{S_2} \\ exp\left[-\left(\frac{x - m_{S_1}}{\sigma_{S_1}^R}\right)^2\right], & if\ x > m_{S_1} \end{cases} \tag{17}$$

According to Figure 3, the intersection of two Gaussian functions is as follows:

$$v = \begin{cases} exp\left[-\left(\frac{m_{S_2} - m_{S_1}}{\sigma_{S_1}^L + \sigma_{S_2}^R}\right)^2\right], & if\ m_{S_1} > m_{S_2} \\ exp\left[-\left(\frac{m_{S_2} - m_{S_1}}{\sigma_{S_1}^L + \sigma_{S_2}^R}\right)^2\right], & if\ m_{S_1} < m_{S_2} \end{cases} \tag{18}$$

The degree of possibility of $S_2 = \mu_{S_2}(x) \ge S_1 = \mu_{S_1}(x)$ is formulated as follows:

$$V(S_2 \ge S_1) = hgt(S_1 \cap S_2) = \mu_{S_2}(X_{int}) \tag{19}$$

$$V(S_2 \ge S_1) = \begin{cases} 1, & if\ m_{S_2} \ge m_{S_1} \\ exp\left[-\left(\frac{m_{S_2} - m_{S_1}}{\sigma_{S_1}^L + \sigma_{S_2}^R}\right)^2\right], & if\ m_{S_1} < m_{S_2} \end{cases} \tag{20}$$

where X_{int} states the ordinate of the interior intersection $\mu_{S_1}(x)$ and $\mu_{S_2}(x)$. Since S_1 and S_2 must be compared with each other, $(S_2 \ge S_1)$ and $(S_1 \ge 2)$ must be known.

Step 3: In this step, the degree of possibility for S_i is determined. The degree of possibility for S_i (a Gaussian fuzzy number) to be greater than k Gaussian fuzzy numbers S_i $(i = 1,2,\ldots,k)$ can be stated as:

$$V(S_2 > S_1, S_2, \ldots, S_k) = V[S > S_1, (S > S_1), \ldots, (S > S_k)] = minV(S > S_i) \tag{21}$$

4. Implementation

Falls from height in shipyards are accidents that result in death or serious injury. Therefore, their causes must first be comprehensively examined. In this study, after a comprehensive literature review and brainstorming sessions, the main criteria for falls from height accidents are as follows: human risks (H), shipyard area and environmental risks (E), organizational risks (O), and safety risks (S). Each main criterion also includes seven sub-criteria. Table 1 presents the main criteria and sub-criteria with their abbreviations. Figure 4 shows the hierarchical design of the causes of falls in shipyards.

Table 1 is important for application in this study. The main criteria and sub-criteria are carefully established after a comprehensive literature search and brainstorming sessions. Then, experts compare all the criteria.

In this study, five-level linguistic variables are used for pairwise comparison. Experts compare all criteria pairwise with the help of linguistic variables. Linguistic variables and the corresponding triangular numbers and Gaussian values are given in Table 2.

For pairwise comparisons of the criteria in Figure 4, an online e-questionnaire is prepared via Google Forms. This e-questionnaire was given to experts with field experience in shipyards, and six experts responded. Two of these experts are academicians working in maritime departments of universities, two currently work as naval architecture and marine engineers in shipyards, and the last two work as occupational safety specialists in shipyards. The names and institutions of the experts are not revealed owing to ethnic concerns. Undoubtedly, each of these experts has a different

Table 1. *Main criteria and sub-criteria for this study*

Main criteria	Sub-criteria	Definition of the sub-criteria
Human risks (H)	**H1**	Slipping or loss of balance as a result of a distraction when working at a height [3,27]
	H2	Unconsciously working with fatigue or apathy at a height [3]
	H3	Unauthorized access to hazardous areas [23]
	H4	Lack of ability and experience or ignorance
	H5	Poor posture control when working at a height [41]
	H6	Employees not caring or using personal protective equipment (PPE) with the "nothing will happen to me" approach
	H7	Saving-the-day approach of the employer
Shipyard area and environment risks (E)	**E1**	Unprotected or unclosed openings on board [23,24]
	E2	The physical conditions at the current height (heat, humidity, lighting level, ventilation) [7,9,23]
	E3	The physical condition of fixed scaffolds (carelessly erected scaffolds, unprotected scaffolds, scaffolds whose frame structures are inappropriate materials and conditions)
	E4	Wheeled mobile scaffolds without a brake system [3]
	E5	The physical condition of fixed ladders (handrails that are not strong enough or lack non-slip material on the steps)
	E6	Presence of too many workers in insufficient areas because the workload exceeds the field capacity
	E7	Bumpy and restricted walkway [23]
Organizational risks (O)	**O1**	Lack of employee training related to working at a height (not giving enough vocational training to the employee)
	O2	Lack of control, supervision, and managerial coordination in shipyards [28]
	O3	Lack of risk assessment and an emergency action plan
	O4	Subcontractor effect in the shipyard (too many subcontractors or risky work performed by subcontractors)
	O5	Poor work practices [23]
	O6	Failure to give clear instructions to employees by determining the appropriate operation method
	O7	Status of the employee working at heights (assigning working at heights to a worker who cannot do so)
Safety risks (S)	**S1**	Inadequate safety/health management
	S2	Failure to provide safety awareness to workers by not providing adequate occupational health and safety (OHS) training [28]
	S3	Failure to prepare and use OHS caution signs
	S4	Lack of the required health certificate of the employee
	S5	Broken PPE [23]
	S6	Failure to ensure that employees use PPE appropriately
	S7	Ignoring the periodic maintenance of KDDs used during working at a height

perspective on the problem. Therefore, this study assumes that the expert weighting scores are not equal.

Ünver et al. [42] propose an approach to calculating expert weighting scores. According to this approach, each expert has parameters such as professional position, work experience, and educational level. These parameters and corresponding scores are given in Table 3. Table 4 presents the calculated weighting scores of the experts. Expert weighting scores are used just before converting individual judgment matrices to aggregated decision matrices. For example, the weighting score for expert 1 is 0.152, and suppose his/her response in any pairwise comparison is *ST*. The corresponding fuzzy number of *ST* is (5,7,9) according to Table 2. Score 0.152 is taken as the exponential value of the fuzzy number. That is, the fuzzy number (5,7,9) turns into the number $(5^{0.152}, 7^{0.152}, 9^{0.152})$. Then, the individual pairwise

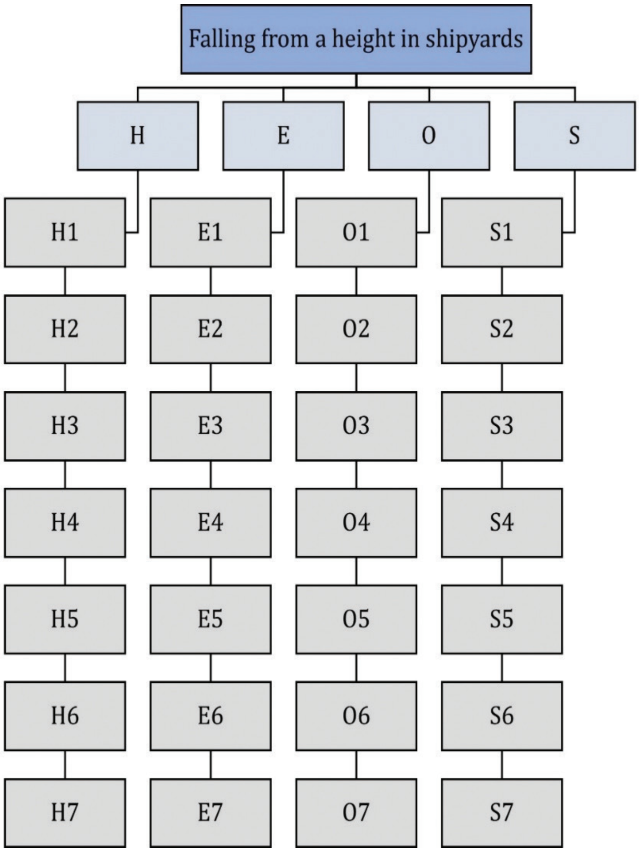

Figure 4. *Hierarchical design of the causes of falls in shipyards*

comparison matrices are converted into aggregated judgment matrices using the geometric mean method. Thus, each expert affects the aggregated decision matrix as much as the weighting score.

The aggregated decision matrices are given in Tables 5, 6, 7, 8, and 9. Table 5 and Tables 6, 7, 8, and 9 present the combined fuzzy number and CCI values for the main criteria and the sub-criteria, respectively. The results of CCI in these tables are less than the crucial value of 0.37. Thus, the aggregated judgment matrices are consistent. Finally, an analysis of aggregated decision matrices is conducted using Gaussian FAHP. To perform these analyzes, the equations in Section 2.6 are used.

5. Results and Discussion

In this study, a risk analysis is carried out by determining the four main criteria and 28 sub-criteria for accidental falls, which is the major cause of death in shipyards. Six experts from the field of shipbuilding compare these main criteria and sub-criteria pairwise. The experts do not have equal weights, and each of them is assigned a weighting score through the expert weighting process. Moreover, the consistency of all obtained individual pairwise comparison judgments and aggregated decision matrices is provided by the expert consistency process. Finally, the Gaussian FAHP method analyzes the aggregated decision matrices and ranks the criteria.

Table 2. *Triangular and Gaussian numbers for linguistic variables (σ=0.1)*

Linguistic variables	Symbol	Crisp no.	Triangular (x,a,b,c)	Gaussian (x,μ,σ)
Equally risky	EQ	1	(x,1,1,1)	(x,1,0.25)
Moderately risky	MD	3	(x,1,3,5)	(x,3,0.25)
More risky	MR	5	(x,3,5,7)	(x,5,0.25)
Strongly risky	ST	7	(x,5,7,9)	(x,7,0.25)
Extremely risky	EX	9	(x,7,9,9)	(x,9,0.25)

Table 3. *Parameters for anonymous experts and their corresponding scores*

Parameters	Classification	Score
Professional position	Occupational safety specialist	3
	Naval architecture engineering	2
	Academic staff	1
Work experience (year)	>10	3
	5-10	2
	<5	1
Educational level	Ph.D.	3
	M.Sc.	2
	B.Sc.	1

Table 4. *Weighting scores for experts*

Experts	Professional position	Work experience (year)	Educational level	Weighting factor			Total weight	Weighting score
1	Academic staff	5-10	M.Sc.	1	2	2	5	0.152
2	Academic staff	<5	M.Sc.	1	2	1	4	0.121
3	Naval architecture engineering	5-10	B.Sc.	2	2	1	5	0.152
4	Naval architecture engineering	<5	B.Sc.	2	1	1	4	0.121
5	Occupational safety specialist	>10	M.Sc.	3	3	2	8	0.242
6	Occupational safety specialist	5-10	M.Sc.	3	2	2	7	0.212

Table 5. *Aggregated judgment matrix for main criteria*

	H	E	O	S
H	(1.00, 1.00, 1.00)	(1.04, 1.13, 1.20)	(0.91, 0.97, 1.02)	(1.03, 1.06,1.10)
E	(0.83, 0.88, 0.96)	(1.00, 1.00, 1.00)	(0.82, 0.87, 0.96)	(0.80, 0.87,0.96)
O	(0.98, 1.03, 1.10)	(1.04, 1.15, 1.22)	(1.00, 1.00, 1.00)	(1.00, 1.04,1.08)
S	(0.91, 0.94, 0.97)	(1.04, 1.14, 1.26)	(0.93, 0.96, 1.00)	(1.00,1.00, 1.00)
CCI	**0.00019**			

Table 6. *Aggregated matrix for human risks (H)*

	H1	H2	H3	H4	H5	H6	H7
H1	(1.00,1.00,1.00)	(1.11,1.14,1.18)	(1.04,1.10,1.15)	(0.96,1.03,1.10)	(1.17,1.25,1.31)	(0.77,0.80,0.87)	(1.05,1.14,1.23)
H2	(0.85,0.87,0.90)	(1.00,1.00,1.00)	(0.81,0.85,0.90)	(0.81,0.85,0.92)	(1.17,1.24,1.31)	(0.70,0.72,0.77)	(1.08,1.14,1.19)
H3	(0.87,0.91,0.97)	(1.11,1.18,1.23)	(1.00,1.00,1.00)	(0.85,0.91,0.98)	(0.98,1.04,1.09)	(0.77,0.79,0.83)	(0.94,0.99,1.05)
H4	(0.91,0.97,1.04)	(1.09,1.17,1.24)	(1.03,1.10,1.18)	(1.00,1.00,1.00)	(1.28,1.36,1.43)	(0.80,0.83,0.87)	(1.03,1.13,1.22)
H5	(0.77,0.80,0.86)	(0.77,0.81,0.85)	(0.91,0.97,1.02)	(0.70,0.73,0.78)	(1.00,1.00,1.00)	(0.69,0.71,0.75)	(0.90,0.97,1.02)
H6	(1.15,1.25,1.30)	(1.30,1.38,1.43)	(1.21,1.26,1.29)	(1.15,1.21,1.25)	(1.34,1.41,1.44)	(1.00,1.00,1.00)	(1.27,1.37,1.41)
H7	(0.81,0.88,0.96)	(0.84,0.88,0.93)	(0.96,1.01,1.07)	(0.82,0.89,0.97)	(0.98,1.03,1.11)	(0.71,0.73,0.79)	(1.00,1.00,1.00)
CCI	**0.0008**						

Table 7. *Aggregated matrix for shipyard area and environmental risks (E)*

	E1	E2	E3	E4	E5	E6	E7
E1	(1.00,1.00,1.00)	(1.25,1.32,1.35)	(1.08,1.12,1.14)	(1.21,1.30,1.35)	(1.07,1.16,1.25)	(1.13,1.21,1.28)	(1.07,1.12,1.16)
E2	(0.74,0.76,0.80)	1(.00,1.00,1.00)	(0.73,0.76,0.79)	(1.11,1.19,1.24)	(0.76,0.81,0.89)	(0.86,0.93,1.01)	(1.02,1.11,1.17)
E3	(0.87,0.90,0.93)	(1.26,1.32,1.36)	(1.00,1.00,1.00)	(1.22,1.34,1.40)	(1.00,1.06,1.14)	(1.19,1.31,1.39)	(1.22,1.33,1.40)
E4	(0.74,0.77,0.82)	(0.81,0.84,0.90)	(0.71,0.75,0.82)	(1.00,1.00,1.00)	(0.77,0.82,0.87)	(0.82,0.87,0.93)	(0.95,1.01,1.09)
E5	(0.80,0.86,0.94)	(1.13,1.23,1.32)	(0.88,0.94,1.00)	(1.15,1.22,1.29)	(1.00,1.00,1.00)	(1.05,1.15,1.22)	(1.00,1.09,1.13)
E6	(0.78,0.82,0.88)	(0.99,1.08,1.16)	(0.72,0.76,0.84)	(1.07,1.15,1.22)	(0.82,0.87,0.95)	(1.00,1.00,1.00)	(0.95,1.01,1.08)
E7	(0.87,0.90,0.93)	(0.86,0.90,0.99)	(0.71,0.75,0.82)	(0.92,0.99,1.05)	(0.88,0.92,1.00)	0.93,0.99,1.05	(1.00,1.00,1.00)
CCI	**0.0009**						

Table 8. *Aggregated matrix for organizational risks (O)*

	O1	O2	O3	O4	O5	O6	O7
O1	(1.00,1.00,1.00)	(0.78,0.81,0.87)	(1.03,1.19,1.27)	0.85,0.92,1.00	(0.95,1.02,1.10)	(0.86,0.90,0.95)	0.79,0.81,0.86
O2	(1.15,1.24,1.28)	(1.00,1.00,1.00)	(1.27,1.37,1.41)	1.17,1.21,1.23	(1.01,1.09,1.14)	(1.10,1.15,1.20)	1.08,1.15,1.21
O3	(0.79,0.84,0.97)	(0.71,0.73,0.79)	(1.00,1.00,1.00)	0.82,0.87,0.97	(0.77,0.84,0.97)	(0.77,0.81,0.90)	0.75,0.78,0.85
O4	(1.00,1.08,1.18)	(0.81,0.82,0.86)	(1.04,1.15,1.22)	1.00,1.00,1.00	(0.89,0.96,1.03)	(0.85,0.91,0.98)	0.92,0.97,1.05
O5	(0.91,0.98,1.05)	(0.88,0.92,0.99)	(1.03,1.19,1.30)	0.98,1.04,1.12	(1.00,1.00,1.00)	(0.88,0.93,1.00)	0.93,0.98,1.07
O6	(1.05,1.11,1.16)	(0.83,0.87,0.91)	(1.11,1.24,1.31)	1.03,1.09,1.18	(1.00,1.08,1.13)	(1.00,1.00,1.00)	0.99,1.03,1.09
O7	(1.16,1.23,1.27)	(0.83,0.87,0.93)	(1.18,1.29,1.34)	0.96,1.03,1.08	(0.94,1.02,1.07)	(0.92,0.97,1.01)	1.00,1.00,1.00
CCI	**0.0004**						

Table 9. *Aggregated matrix for security risks (S)*

	S1	S2	S3	S4	S5	S6	S7
S1	(1.00,1.00,1.00)	(0.82,0.85,0.91)	(1.10,1.19,1.27)	(1.24,1.34,1.40)	(1.07,1.11,1.15)	(0.87,0.95,1.02)	1.05,1.13,1.19
S2	(1.10,1.17,1.23)	(1.00,1.00,1.00)	(1.21,1.29,1.36)	(1.34,1.41,1.43)	(0.97,1.03,1.08)	(0.93,0.96,1.00)	1.19,1.27,1.33
S3	(0.78,0.84,0.91)	(0.73,0.78,0.83)	(1.00,1.00,1.00)	(1.11,1.20,1.26)	(0.83,0.91,0.98)	(0.76,0.80,0.85)	0.75,0.79,0.86
S4	(0.71,0.75,0.81)	(0.70,0.71,0.75)	(0.79,0.83,0.90)	(1.00,1.00,1.00)	(0.75,0.78,0.84)	(0.71,0.75,0.81)	0.72,0.76,0.84
S5	(0.87,0.90,0.94)	(0.92,0.97,1.03)	(1.02,1.10,1.20)	(1.19,1.28,1.34)	(1.00,1.00,1.00)	(0.85,0.90,0.98)	1.00,1.06,1.14
S6	(0.98,1.05,1.15)	(1.00,1.04,1.08)	(1.17,1.25,1.31)	(1.23,1.34,1.41)	(1.02,1.11,1.17)	(1.00,1.00,1.00)	1.15,1.22,1.28
S7	(0.84,0.89,0.95)	(0.75,0.79,0.84)	(1.16,1.26,1.33)	(1.19,1.32,1.39)	(0.88,0.94,1.00)	(0.78,0.82,0.87)	1.00,1.00,1.00
CCI	**0.0007**						

The weightings of the main criteria are presented in Figure 5. Accordingly, human risks (H) are determined the primary risk criteria in accidental falls, at 27.77%. Organizational risks (O) (25.80%) and safety risks (S) (25.55%) are almost equally weighted. Shipyard area and environment risks (E) are calculated as 22.89%.

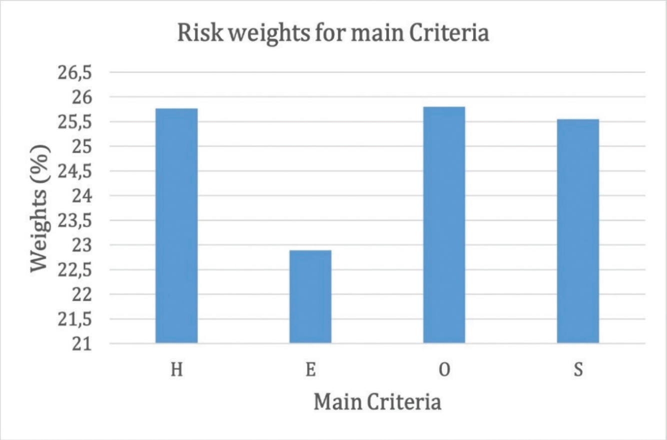

Figure 5. *Risk values for main criteria*

As a result of the data analysis, the weights of all sub-criteria are found. Employees not caring or not using personal protective equipment (PPE) with the "nothing will happen to me" approach (H6) was determined the riskiest criterion in the human (H) risks. According to the significance level, the human risks are ranked as H6 > H4 > H1 > H3 > H2 > H7 > H5. The risk sequence for the shipyard area and environment (E) is E3 > E1 > E5 > E6 > E2 > E7 > E4. Thus, the physical condition of fixed scaffolds (E3) is the most crucial criterion in the shipyard area and environment (E) risks. According to importance weight, the organizational-related (O) risks are ranked as O2 > O6 > O7 > O5 > O4 > O1 > O3. This result shows that a lack of control, supervision, and managerial coordination in shipyards (O2) is the riskiest criterion in the organizational-related (O) risks. Finally, in safety risks (S), failure to provide safety information to workers by not providing adequate Occupational Health and Safety (OHS) training (S2) was determined as the riskiest criterion. According to importance weight, the safety-related (S) risks are ranked as S2 > S6 > S1 > S5 > S7 > S3 > S4. The relative and percentage weights for all criteria are presented in Table 10.

The relative weights of all sub-criteria are given in Figure 6. Considering the relative values of all sub-criteria, H1 was determined as the riskiest criterion, at 5.09%. This result shows that not heeding PPE use with the logic of "nothing will happen to me" of the employees working at heights

***Table 10**. Risk weights for all criteria*

Criteria	Weight	Relative weight	Percentage weight	Criteria	Weight	Relative weight	Percentage weight
H	0.2577	-	25.77	O	0.2580	-	25.80
H1	0.1658	0.0427	4.2736	O1	0.1326	0.0342	3.4215
H2	0.1273	0.0328	3.2796	O2	0.1666	0.0430	4.2990
H3	0.1349	0.0348	3.4772	O3	0.0972	0.0251	2.5067
H4	0.1700	0.0438	4.3803	O4	0.1420	0.0366	3.6624
H5	0.0902	0.0232	2.3246	O5	0.1467	0.0378	3.7840
H6	0.1978	0.0510	5.0970	O6	0.1576	0.0406	4.0648
H7	0.1139	0.0294	2.9356	O7	0.1574	0.0406	4.0599
E	0.2289	-	22.89	S	0.2555	-	25.55
E1	0.1708	0.0391	3.9088	S1	0.1614	0.0412	4.1236
E2	0.1293	0.0296	2.9590	S2	0.1661	0.0424	4.2423
E3	0.1708	0.0391	3.9090	S3	0.1201	0.0307	3.0689
E4	0.1065	0.0244	2.4377	S4	0.0852	0.0218	2.1766
E5	0.1621	0.0371	3.7099	S5	0.1538	0.0393	3.9284
E6	0.1356	0.0310	3.1046	S6	0.1658	0.0424	4.2360
E7	0.1249	0.0286	2.8588	S7	0.1476	0.0377	3.7702

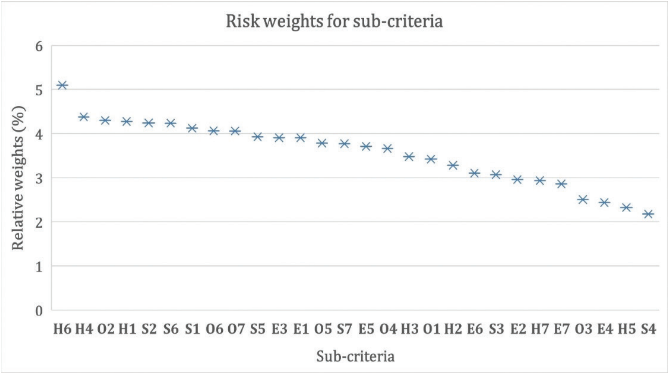

***Figure 6.** Risk values for sub-criteria*

in shipyards causes more such fatalities. H4, a human (H) risk factor, was determined as the second most risky sub-criterion in accidental falls, at 4.38%. This result shows that experience, knowledge, and skill level are important factors in accidental falls. Therefore, qualifications such as experience, knowledge, and skill level should be at a high level for employees working at heights. O2, an organizational risk factor, is the third riskiest sub-criterion in accidental falls, at 4.29%. According to this result, lack of control, supervision, and managerial coordination is critical for accidental falls in shipyards. H1 (slipping or loss of balance due to distraction when working at a height) was determined as the fourth riskiest sub-criterion, at 4.27%. S2 (failure to provide safety awareness in workers by not providing adequate OHS training) was fifth, at 4.24%. Three of the five riskiest sub-criteria are human risks, while the others are organizational and security-related risks. It is possible to say that human (H) risks are more critical in accidental falls in shipyards.

6. Conclusion

Falling from a height is one of the accidents with the highest probability of resulting in death or serious injury in shipyards and similar construction industries. Such accidents cannot be exactly prevented, but they can be minimized. Therefore, the causes of these accidents need to be examined in detail.

In this study, four main criteria and 28 sub-criteria are determined as the causes of accidental falls in shipyards through a comprehensive literature review and brainstorming sessions. Then, a solution methodology is presented to calculate the weight of each main criterion and sub-criterion on accidental falls. For data collection, an e-questionnaire was prepared via Google Forms so that experts could compare all criteria pairwise in linguistic form. Moreover, a proposed solution methodology with an expert weighting process and an expert consistency process is included. The expert consistency process ensures that all individual and aggregated judgments are consistent, while the expert weighting process ensures that each expert has a different weight score. Finally, all criteria are ranked using the Gaussian AHP method in the data analysis step.

According to the findings of this study, the five riskiest criteria are as follows: H6 (employees not caring or not using PPE with the "nothing will happen to me" approach), H4 (lack of ability and experience or ignorance), O2 (lack of control, supervision, and managerial coordination in shipyards), H1 (slipping or loss of balance as a result of a distraction when working at a height), and S2 (failure to provide safety awareness in workers by not providing adequate OHS training). Three of these five criteria are human risks, indicating that human risks are critical in such accidents.

Many safety measures are taken for accidental falls in shipyards. These safety measures develop with technology. However, there will always be a risk of these accidents occurring unless the perspective on safety measures changes for those who work at heights. Workers working at heights should be aware that their life is very precious. Teaching workers this awareness is the best safety measure that can be taken. In this study, the determination of the riskiest criterion as H6 (employees not caring or using PPE with the "nothing will happen to me" approach) is evidence of this situation. Furthermore, shipyards should also strive to increase this awareness.

Future research directions are proposed to overcome the limitations of this study.

(i) In this study, only Gaussian AHP is used to overcome the problem. Subsequent research can apply different methods and integrated approaches.

(ii) This study presents a basic analysis including percentages and rankings for all criteria. A more in-depth analysis can be conducted using methods such as correlation and sensitivity analysis.

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Crossover Operators in a Genetic Algorithm for Maritime Cargo Delivery Optimization

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Abstract

Maritime cargo delivery accounts for over 80% of the world's trade and contributes about 3% of the world's gross domestic product. Here, we focus on the problem of minimizing the maritime cargo delivery cost by an amount equivalent to the sum of the tour lengths of feeders used for the delivery. We formulate maritime cargo delivery cost reduction as a multiple traveling salesman problem and use a genetic algorithm to solve it. In addition to minimizing the route length, the algorithm indirectly reduces the number of feeders. To increase the performance of the genetic algorithm, we implement a 3-point crossover operator, which takes three chromosomes and returns slightly more complex crossover mutations than the known 2-point crossover operator. These two operators must be used in confluence. We propose to run both the 2-point crossover algorithm and the 2-point-and-3-point crossover algorithm in parallel and select the route with the shortest length. The route length is cut down by a few percent, which makes a big difference in how much it costs to ship cargo by sea.

Keywords: Maritime cargo delivery, Tour length, Genetic algorithm, Crossover

1. Introduction

Maritime transportation is the basis of the world trade and commerce. Approximately 80% of all goods are transported by river, sea, and ocean. The global cargo shipping market was valued at $11.36 billion in 2021, and it is expected to reach $16.43 billion by 2029. This corresponds to a compound annual growth rate of 4.72% during the forecast period of 2022-2029 [1]. According to United Nations Conference on Trade and Development [2], shipping is responsible for more than 80% of the globe's trade, and the total contribution of the industry to the global economy is estimated at 3% of the globe's gross domestic product. In addition to the market insights such as market value, growth rate, market segments, geographical coverage, market players, and market scenario, the market report supported by the Data Bridge Market Research team also includes in-depth expert analysis, import/export analysis, pricing analysis, production consumption analysis, and PESTLE (PESTLE stands for political, economic, social, technological, legal, and environmental) analysis [3].

The maritime delivery market is divided into regions, each of which represents an important part of the entire market. The Mediterranean Sea is an important maritime and commercial route, containing 87 ports of various sizes and strengths servicing local, regional, and international markets. The Asia-Pacific region is considered the manufacturing hub for automotive companies. Regionally and globally, China holds the largest market share for cargo shipping. There are 34 major and more than 2000 minor ports in China. All the 926 ports in the United States are essential to the nation's competitiveness, as 99% of overseas trade travels through them. The Middle East and Africa are also expected to show augmented growth in the market. Improved port connections and a greater emphasis on modernizing and expanding existing ports have boosted the amount of trade in this region [4].

A. P. Moller-Maersk [5], Mediterranean Shipping Company [6], China COSCO Shipping [7], and CMA CGM Group [8] are the key players whose market share in terms of deployed capacity exceeds 10%. Hapag-Lloyd, ONE, Evergreen, Yang

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Ming, Pacific International Lines, and Hyundai [2] complete the top 10 deep-sea container shipping lines, with a market share greater than 2% (but less than 9%; the shipping lines are listed in descending order). According to the review of maritime transport, published by the United Nations Conference on Trade and Development in 2019, three major alliances account for nearly 87% of the cargo shipped on the transpacific route, 98% of the Asia-Europe trade, and about 80% of the containership capacity deployed globally [2].

Cargo shipping is a means of transportation used to convey commodities, goods, cargo, etc., from a seaport to a destination through vessels, cargo ships, and others. Shipping is the cheapest means of transportation per ton. It is preferred due to its economic and environmental friendliness in long-distance transportation. Increasing orders for the import/export of manufactured goods, the transportation of raw materials in bulk, and affordable food items fuel the demand for waterborne freight transportation. The expansion of the global supply chain, the liberalization of trade policies, and technological advancement in waterborne shipping have propelled the trade of intermediate and manufactured products and significantly reduced coordination and transportation costs. To maximize the potential of maritime transportation, it is necessary to plan efficient tours. Typically, a tour consists of one or more hubs, which serve as a starting point, and many ports, which function as local destinations for cargo delivery. A route comprised of tours should be divided as rationally as possible between feeder ships (medium-sized freight ships) and route-based tours (having a minimal length and being covered by a minimal number of feeders). The efficient tour has the smallest length possible, expressed in either distance or time units (or both). Minimizing the tour length is a transportation optimization problem [9]. This is a version of the traveling salesman problem applicable to cargo shipping [10], where feeder ships must be freighted at the hub, deliver their cargo, and return to the hub (in addition, they can be re-freighted with cargo at some ports heading toward the hub). Recent studies have investigated different approaches to solving this problem, including deterministic, meta-heuristic, and market-based approaches [9,11]. However, heuristic-based approaches that offer greater advantage in computational efficiency are the cutting edge in rational routing [12]. Only a few exact method approaches have been introduced in recent years [13]. Therefore, heuristics with their combinations (metaheuristics) and extensions (matheuristics) are typically sufficient for route optimization tasks.

2. Literature Overview and Motivation

An exact solution to the traveling salesman problem routes efficient tours. Such routing minimizes the cost of maritime delivery. The traveling salesman problem is an NP-hard problem in combinatorial optimization [14]. An exact solution to the traveling salesman problem usually takes too long to be obtained because an exact algorithm performs reasonably fast only for small-sized problems [15]. Finding the exact solution becomes exponentially intractable as the number of ports (sometimes referred to as cities) is increased, starting with a few tens [11,14]. Heuristic algorithms produce approximate solutions far more quickly. The difference between an approximate solution and an exact solution is usually acceptable [12,16]. It is highly probable that an approximate solution given by a heuristic is at most 3% away from the optimal solution, even for large routing problems (with thousands of ports and cities) [11,17]. Meanwhile, heuristic algorithms immensely save computational resources equivalent to operational time [14,15]. Rerouting maritime delivery tours when it is urgent has a significant economic impact.

The genetic algorithm is one of the greatest heuristics since it allows for the discovery of tours whose length is practically close to the minimal length of the delivery [17,18]. Usually, it is faster than the algorithms of ant colony optimization, simulated annealing, and tabu search while maintaining the same accuracy [9,14,19]. For maritime cargo delivery using multiple tours covered by multiple feeder ships, the genetic algorithm inputs are a map of ports, a number of feeders, a population size, mutation operators, and a series of additional minor parameters. The map of ports is the two-coordinate location of ports that should be visited en route. The number of feeders defines the maximum number of tours by which the cargo can be delivered. The population size is the number of randomly generated tours to be processed by the algorithm. The mutation operators are intended to occasionally break one or more members of a population out of the local minimum space and potentially discover a better minimum space.

The crossover is a convergence operation designed to pull the population toward a local minimum [18,20]. The majority of genetic algorithms use single-point crossovers. Single-point crossover is a technique where the selected parent population, i. e., the two mating chromosomes, is cut at a randomly selected location known as the pivot point or crossover point. At this cut, the genetic information to the left (or right) of the point is swapped between the two parent chromosomes to produce two offspring chromosomes (children). This technique becomes more robust if each parent has its own pivot point. These pivot points are also selected at random. Then it is a 2-point crossover mutation, although it is sometimes still referred to as a single-point crossover (due to every parent is cut at a single point) [17,18,21]. A 2-point crossover mutation increases performance of the genetic algorithm by accelerating convergence and shortening route lengths. Therefore, it may be expected that a more complex operation of crossover mutations can result in an even greater performance boost.

Therefore, the goal is to try a more complex crossover mutation to improve the performance of the genetic algorithm. This is believed to have a significant impact on the future rationalization of maritime transportation route design to improve maritime cargo shipping and delivery. To achieve the goal, the following six tasks need to be fulfilled:

1. Introduce and explain the variables and denotations used in the genetic algorithm for a maritime cargo delivery model.
2. Formalize the genetic algorithm using 2-point crossover mutations.
3. Suggest a more complex operation of crossover mutations based on the fact that multiple feeders are used for maritime cargo delivery.
4. Evaluate how the algorithm with the suggested crossover mutation operation performs in comparison with the known 2-point crossover mutation operation.
5. Explore the practical applicability and significance of the suggested crossover mutation operation in the genetic algorithm.
6. Conclude on the contribution to the field of genetic algorithms used in optimizing maritime cargo delivery. Outline a possible extension of the research.

The rest of this paper is organized as follows: A model of maritime cargo delivery is presented in Section 3. Section 4 formalizes a genetic algorithm using a 2-point crossover mutation operator. The 2-point crossover mutation is additionally explained with a visual example. Section 5 introduces our 3-point crossover mutation operator, accompanied by a visual illustration of the 3-point crossover mutation. The testing results for both 2-point and 3-point crossover operators are presented and analyzed in Section 6. Our contribution is discussed in Section 7, whereupon we conclude with the main findings in Section 8.

3. Maritime Cargo Delivery Model

Denote by N a number of ports, from one of which every feeder starts its tour and ends up by returning to that port. By default, the port is assigned number 1 and is called the hub. The positions or coordinates of all N ports are known. These positions are naturally presumed to be flat because no ship can ascend or descend. For port k, denote them by p_{k1} (the horizontal position) and p_{k2} (the vertical position). Positions of all the ports are gathered in matrix

$$\mathbf{P} = [p_{kl}]_{N\times 2}\,. \tag{1}$$

It is assumed that if a feeder must go from port k to port j, without additional stops, then the feeder accomplishes it in a straight line. Therefore, the distance covered by the feeder from port k directly to port j (or in the opposite direction) is

$$\rho(k,j) = \sqrt{(p_{k1}-p_{j1})^2 + (p_{k2}-p_{j2})^2} = \rho(j,k)$$

$$\text{by } k=\overline{1,N} \text{ and } j=\overline{k+1,N}\,. \tag{2}$$

Formally,

$$\rho(k,k)=0 \quad \forall k=\overline{1,N}\,. \tag{3}$$

It is quite natural to assume that the speed of every feeder heading for a port is (roughly) constant.

Then these $\frac{N(N-1)}{2}$ non-zero distances

$$\left\{\left\{\rho(k,j)\right\}_{k=1}^{N}\right\}_{j=k+1}^{N} \tag{4}$$

in (2) can be easily mapped into durations of the maritime cargo delivery. The durations can be subsequently mapped into the respective costs of the delivery. The general aim is to minimize such costs.

Denote by $M_{\max}$ the number of feeders available to accomplish the delivery. Usually, there are at least two available feeders. Hence, $M_{\max} \in \mathbb{N}\setminus\{1\}$. However, an additional aim is to enable as less feeders as possible.

If feeder m visits either port j after port k or port k after port j (the direction here does not matter), then this fact is featured with a flag: $x_{kjm} = 1$. To exclude repeated flags in the case when feeder m visits more than one port (apart from the hub), we assign $x_{jkm} = 0$ if $x_{kjm} = 1$ and $x_{kjm} = 0$ if $x_{jkm} = 1$. When feeder m leaves the hub to visit only port k and then returns to the hub, we assign $x_{1km} = x_{k1m} = 1$. If feeder m does not visit port j after port k nor port k after port j, then $x_{kjm} = 0$ (although ports k and j still can be included into the tour of feeder m). So, each flag

$$x_{kjm} \in \{0,1\} \text{ by } k=\overline{1,N} \text{ and } j=\overline{1,N} \text{ and } m=\overline{1,M} \tag{5}$$

by a (current) number of feeders M, where $M \leqslant M_{\max}$. Henceforward, we have two first constraints. First, each of M feeders only once departs from the hub:

$$\sum_{j=2}^{N}\sum_{m=1}^{M} x_{1jm} = M\,. \tag{6}$$

Second, each of M feeders only once arrives at the hub:

$$\sum_{k=2}^{N}\sum_{m=1}^{M} x_{k1m} = M\,. \tag{7}$$

Only one feeder can arrive at port j, being not the hub, from only one port (which can be the hub). This constraint is expressed by an equality

$$\sum_{k=1}^{N}\sum_{m=1}^{M} x_{kjm} = 1 \quad \forall j=\overline{2,N}\,. \tag{8}$$

Symmetrically, only one feeder can depart from port *k*, being not the hub, toward only one following port (which can be the hub). This constraint is expressed by an equality

$$\sum_{j=1}^{N}\sum_{m=1}^{M} x_{kjm} = 1 \quad \forall k = \overline{2, N}\,. \tag{9}$$

In addition to constraints (6)-(9), any subtour of a feeder should be eliminated with the following requirement:

$$\sum_{k \in Q_m}\ \sum_{j \in Q_m \setminus \{k\}} x_{kjm} \leqslant |Q_m| - 1$$

$$\forall Q_m \subset T_m \subset \left\{\overline{1, N}\right\} \text{ by } 2 \leqslant |Q_m| < A_m \text{ and } \forall m = \overline{1, M} \tag{10}$$

with tour

$$T_m = \left\{1, \left\{q_l^{(m)}\right\}_{l=2}^{A_m}\right\} \subset \left\{\overline{1, N}\right\} \tag{11}$$

of feeder *m*. The inequality in (10) means that if Q_m is a subtour of tour (11), then its ports are not connected into a closed loop owing to fact that at least one pair of ports are disconnected (it is that term $|Q_m| - 1$). Constraint (10) with (11) ensures that every feeder has a tour as a closed loop: it departs from the hub and arrives at it. Owing to this constraint, a feasible route of delivering maritime cargo is of closed loops only, where every loop is a feeder tour that starts at the hub and ends by returning to the hub.

The sixth constraint is determined by the capacity of the feeder fleet. Obviously, the feeder has a limit on the distance it can cover without a fuel refill. Denote this limit by $d_{\max}$. Therefore, inequality

$$\sum_{k=1}^{N}\sum_{j=1}^{N} \rho(k, j) \cdot x_{kjm} \leqslant d_{\max} \quad \forall m = \overline{1, M} \tag{12}$$

constraints the tour of every feeder. Herein, nevertheless, we do not define the shortest possible tour of the feeder. If a feeder is enabled for delivery, it must (and definitely will) visit at least one port, not the hub.

To optimize maritime cargo delivery, the sum of all the tours of the feeders is to be minimized. The respective objective function

$$\rho_{\Sigma}\left(N, M, \left\{\left\{\left\{x_{kjm}\right\}_{k=1}^{N}\right\}_{j=1}^{N}\right\}_{m=1}^{M}, d_{\max}\right) =$$

$$= \sum_{k=1}^{N}\sum_{j=1}^{N}\sum_{m=1}^{M} x_{kjm} \cdot \rho(k, j) \tag{13}$$

is to be minimized subject to flags (5) and constraints (6)-(12). The minimization is implied to be done over binary variables (5), along with trying to minimize the total number of feeders used in the tours. That is, the minimization objective is to find such

$$M^* \in \left\{\overline{1, M_{\max}}\right\} \tag{14}$$

and

$$x_{kjm}^* \in \{0, 1\} \text{ for } k = \overline{1, N} \text{ and } j = \overline{1, N} \text{ by } m = \overline{1, M^*} \tag{15}$$

at which

$$\sum_{k=1}^{N}\sum_{j=1}^{N}\sum_{m=1}^{M^*} x_{kjm}^* \cdot \rho(k, j) =$$

$$= \rho_{\Sigma}\left(N, M^*, \left\{\left\{\left\{x_{kjm}^*\right\}_{k=1}^{N}\right\}_{j=1}^{N}\right\}_{m=1}^{M^*}, d_{\max}\right) =$$

$$= \min_{\substack{\left\{\left\{x_{kjm}\right\}_{k=1}^{N}\right\}_{j=1}^{N},\\ m=\overline{1, M},\, M=\overline{1, M_{\max}}}} \sum_{k=1}^{N}\sum_{j=1}^{N}\sum_{m=1}^{M} x_{kjm} \cdot \rho(k, j)\ . \tag{16}$$

The solution given formally as

$$\left\{\left\{\left\{x_{kjm}^*\right\}_{k=1}^{N}\right\}_{j=1}^{N}\right\}_{m=1}^{M^*} \tag{17}$$

allows building a set of M^* the most rational tours of M^* feeders. Sum (16) of these tours is the length of the shortest route to deliver maritime cargo and return to the hub. Nevertheless, the solution to this problem may not be unique. For example, there may be two shortest routes (whose lengths are equal), but one of them can be covered with a lesser number of feeders. Then the route covered by such feeders is usually accepted. An additional criterion to select a route should be formulated if both the shortest routes are covered by the same number of feeders.

4. Algorithm Using 2-point Crossover

There are usually at least a few tens of ports for delivery, so exact methods are intractably time-consuming to find minimal-length routes. The computational task is thus simplified to finding a route whose length is practically close to the shortest route length. An approximately minimal-length route is obtained by a genetic algorithm specifically designed for solving problem (16) subject to flags (5) and constraints (6)-(12) [20]. The primary steps of the algorithm are the random population generation, the currently best result evaluation, and mutations.

Let H_m be the number of ports that feeder *m* should visit after starting off port 1 (the hub), whereupon the feeder returns to the hub (so, the hub is not counted in this number). Consider a vector of ports that feeder *m* should visit in the order of the sequence of the vector elements (apart from the hub). So, this vector

$$\mathbf{F}_m = \left[f_h^{(m)}\right]_{1 \times H_m} \tag{18}$$

is a tour of feeder *m*. Tours $\left\{\mathbf{F}_m\right\}_{m=1}^{M}$ of all feeders constitute a route of delivery (apart from the hub). This means that

$$\bigcup_{m=1}^{M} \left\{f_h^{(m)}\right\}_{h=1}^{H_m} = \left\{\overline{2, N}\right\} \tag{19}$$

due to

$$\left\{\overline{2, N}\right\} \tag{20}$$

is the set of all non-hub ports.

Before the genetic algorithm runs into the first iteration, tours $\{\mathbf{F}_m\}_{m=1}^{M}$ of feeders are randomly generated by breaking the set of non-hub ports (20). Each feeder has a series of such tours called chromosomes. Altogether, such a series of all the feeders constitute a population. Each element of the population is a route of delivery using M feeders represented as M respective chromosomes. For every route of the population, the following routine is executed during an iteration of the algorithm. First, the distance to the port following the hub is calculated as

$$d_m = \rho\left(1, f_1^{(m)}\right) \ . \tag{21}$$

Then, the remaining distances except the last one are accumulated into d_m:

$$d_m^{(\text{obs})} = d_m \, , \ d_m = d_m^{(\text{obs})} + \rho\left(f_k^{(m)}, f_{k+1}^{(m)}\right)$$

$$\text{for } k = \overline{1, H_m - 1} \, . \tag{22}$$

Finally, the distance of returning to the hub is:

$$d_m^{(\text{obs})} = d_m \ , \ d_m = d_m^{(\text{obs})} + \rho\left(f_{H_m}^{(m)}, 1\right) \ . \tag{23}$$

To improve the selectivity of the best feeder tours, tours that violate condition (12) are expunged. Thus, if $d_m > d_{\max}$ then the current accumulated distance d_m after (23) is increased using a factor $\lambda > 0$:

$$d_m^{(\text{obs})} = d_m \ , \ d_m = d_m^{(\text{obs})} + \left(d_m^{(\text{obs})} - d_{\max}\right) \cdot \lambda \, . \tag{24}$$

Finally, sum

$$\tilde{\rho}_{\Sigma}\left(N, M, \{\mathbf{F}_m\}_{m=1}^{M}, d_{\max}\right) = \sum_{m=1}^{M} d_m \geqslant$$

$$\geqslant \rho_{\Sigma}\left(N, M^*, \left\{\left\{\left\{x_{kjm}^*\right\}_{k=1}^{N}\right\}_{j=1}^{N}\right\}_{m=1}^{M^*}, d_{\max}\right) \tag{25}$$

is calculated and minimized over the population to obtain the currently best result. The sum in (25) is the fitness function of the genetic algorithm. A new population is generated based on four forms of chromosome mutation: flip, swap, slide, and crossover [20]. The crossover operator takes two chromosomes (without losing generality)

$$\mathbf{F}_1 = \left[f_h^{(1)}\right]_{1 \times H_1} \tag{26}$$

and

$$\mathbf{F}_2 = \left[f_h^{(2)}\right]_{1 \times H_2} \ , \tag{27}$$

whereupon they are either interchanged or merged. This is done using a merging probability P_{merge} given at the input of the genetic algorithm. If $\theta \leqslant P_{\text{merge}}$, where θ is a random value drawn from the standard uniform distribution on the open interval (0;1), then chromosomes (26) and (27) as tours of two different feeders are merged into a single tour:

$$\mathbf{F}_{1 \cup 2}^* = \left\{f_h^{(1)}\right\}_{h=1}^{H_1} \cup \left\{f_h^{(2)}\right\}_{h=1}^{H_2} \subseteq \left\{\overline{2, N}\right\} . \tag{28}$$

This allows us to decrease the number of feeders used to deliver maritime cargo. Otherwise, if $\theta > P_{\text{merge}}$ then each chromosome is cut into two random parts. If we leave h_1 first ports in the first chromosome, and h_2 in the second chromosome, the remaining parts are interchanged as follows:

$$\mathbf{F}_1^* = \left[f_h^{(1)*}\right]_{1 \times (h_1 + H_2 - h_2)} = \left\{\left\{f_h^{(1)}\right\}_{h=1}^{h_1}, \left\{f_h^{(2)}\right\}_{h=h_2+1}^{H_2}\right\} \tag{29}$$

and

$$\mathbf{F}_2^* = \left[f_h^{(2)*}\right]_{1 \times (h_2 + H_1 - h_1)} = \left\{\left\{f_h^{(2)}\right\}_{h=1}^{h_2}, \left\{f_h^{(1)}\right\}_{h=h_1+1}^{H_1}\right\} . \tag{30}$$

This is a 2-point crossover mutation. An example of a 2-point crossover operation over chromosomes

$$\mathbf{F}_1 = [17 \quad 10 \quad 9 \quad 14 \quad 19 \quad 4 \quad 18 \quad 7 \quad 16 \quad 11]$$

and

$$\mathbf{F}_2 = [2 \quad 8 \quad 15 \quad 6 \quad 5 \quad 12 \quad 3 \quad 13]$$

is shown in Figure 1.

For simplicity, the numbers of chromosomes (26) and (27) are taken as 1 and 2. It does not mean that there are only two feeders left or that only the first two feeders (of $M \geqslant 3$) are subject to crossover mutation. Consequently, if the merging is done by $M \geqslant 3$, single tour (28) is, generally speaking, a part of the route:

$$\mathbf{F}_{1 \cup 2}^* \subset \left\{\overline{2, N}\right\} \text{ and } \mathbf{F}_{1 \cup 2}^* \neq \left\{\overline{2, N}\right\} .$$

On the contrary,

$$\mathbf{F}_{1 \cup 2}^* = \left\{\overline{2, N}\right\}$$

only if $M = 2$ (i. e., there are two feeders left before the 2-point crossover operation). Therefore, the merged two chromosomes constitute a route of delivery (apart from the hub).

5. 3-point Crossover

If the maritime delivery service can afford to use three feeders or more, the crossover mutation can be made more complex. In this way, three chromosomes are simultaneously mutated by exploiting the interchange pattern of the 2-point crossover operation. In certain cases, determined by random value θ, the three chromosomes are merged into a single tour.

Therefore, in a 3-point crossover mutation, without losing generality, the crossover operator takes three chromosomes (26), (27),

$$\mathbf{F}_3 = \left[f_h^{(3)}\right]_{1\times H_3} \tag{31}$$

whereupon they are either interchanged or merged. If $\theta \leqslant P_{\text{merge}}$ then chromosomes (26), (27), and (31) as tours of three different feeders are merged into a single tour

$$\mathbf{F}^*_{1\cup 2\cup 3} = \left\{f_h^{(1)}\right\}_{h=1}^{H_1} \cup \left\{f_h^{(2)}\right\}_{h=1}^{H_2} \cup \left\{f_h^{(3)}\right\}_{h=1}^{H_3} = \left\{\overline{2, N}\right\}. \tag{32}$$

Otherwise, if $\theta > P_{\text{merge}}$ then each chromosome is cut into two random parts; having left h_1, h_2, and h_3 first ports in the first, second, and third chromosomes, respectively, the remaining parts are interchanged:

$$\mathbf{F}_1^* = \left[f_h^{(1)*}\right]_{1\times(h_1+H_3-h_3)} = \left\{\left\{f_h^{(1)}\right\}_{h=1}^{h_1}, \left\{f_h^{(3)}\right\}_{h=h_3+1}^{H_3}\right\} \tag{33}$$

and (30) and

$$\mathbf{F}_3^* = \left[f_h^{(3)*}\right]_{1\times(h_3+H_2-h_2)} = \left\{\left\{f_h^{(3)}\right\}_{h=1}^{h_3}, \left\{f_h^{(2)}\right\}_{h=h_2+1}^{H_2}\right\}. \tag{34}$$

An example of the 3-point crossover operation over chromosomes

$$\mathbf{F}_1 = [22 \quad 18 \quad 11 \quad 20 \quad 14 \quad 4 \quad 12],$$
$$\mathbf{F}_2 = [6 \quad 2 \quad 19 \quad 10 \quad 3 \quad 16],$$
$$\mathbf{F}_3 = [5 \quad 7 \quad 8 \quad 9 \quad 23 \quad 15 \quad 13 \quad 21 \quad 17]$$

is shown in Figure 2.

Once again, the numbers of chromosomes (26), (27), and (31) taken as 1, 2, and 3 for the sake of simplicity do not mean that there are only three feeders left at all or that the 3-point crossover operator takes only the first three feeders (of $M \geqslant 4$). If the merging is done by $M \geqslant 4$, single tour (32) is, generally speaking, a part of the route:

$$\mathbf{F}^*_{1\cup 2\cup 3} \subset \left\{\overline{2, N}\right\} \text{ and } \mathbf{F}^*_{1\cup 2\cup 3} \neq \left\{\overline{2, N}\right\}.$$

On the contrary,

$$\mathbf{F}^*_{1\cup 2\cup 3} = \left\{\overline{2, N}\right\} \tag{35}$$

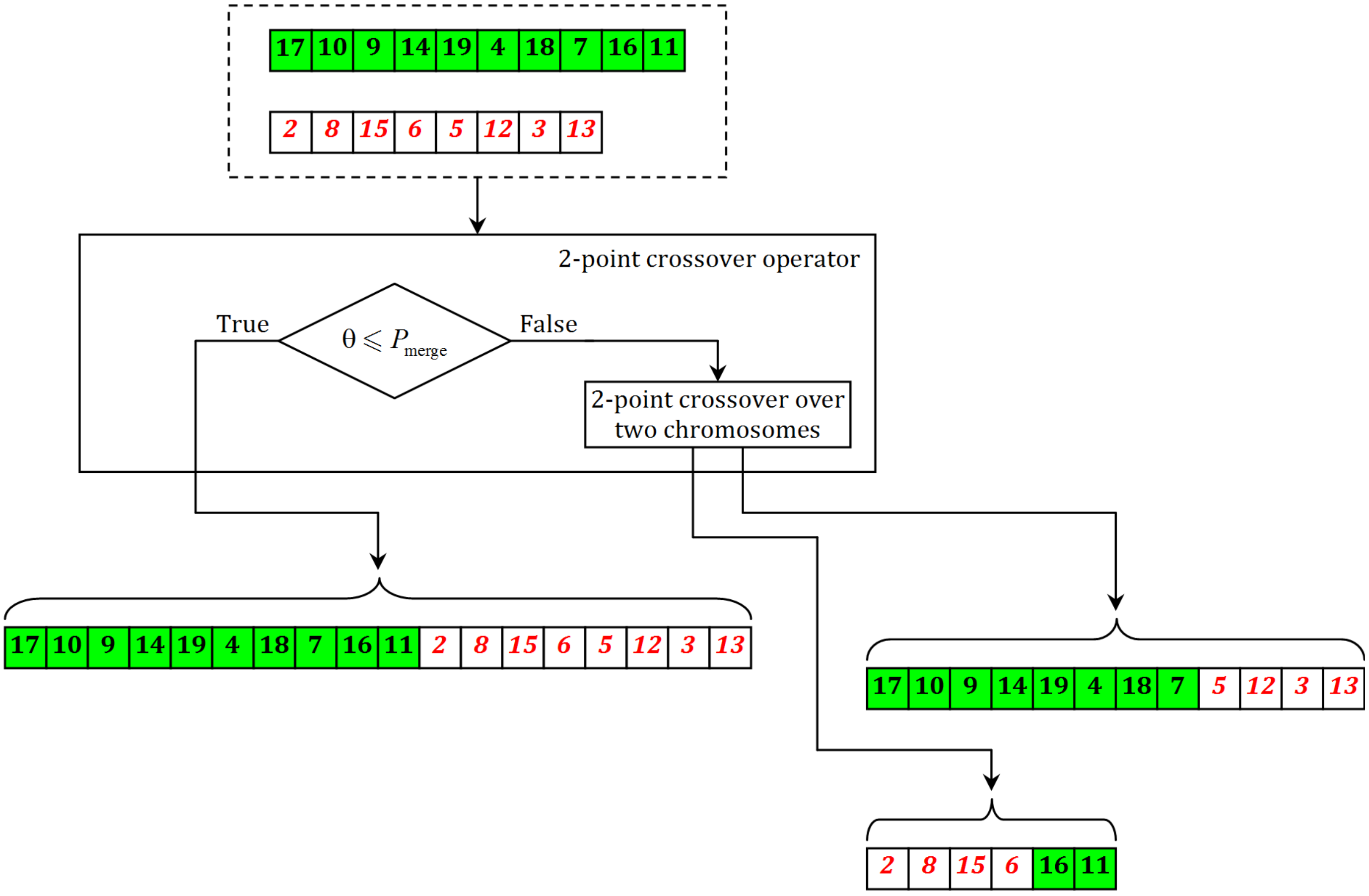

Figure 1. *An example of the 2-point crossover operation over two chromosomes*

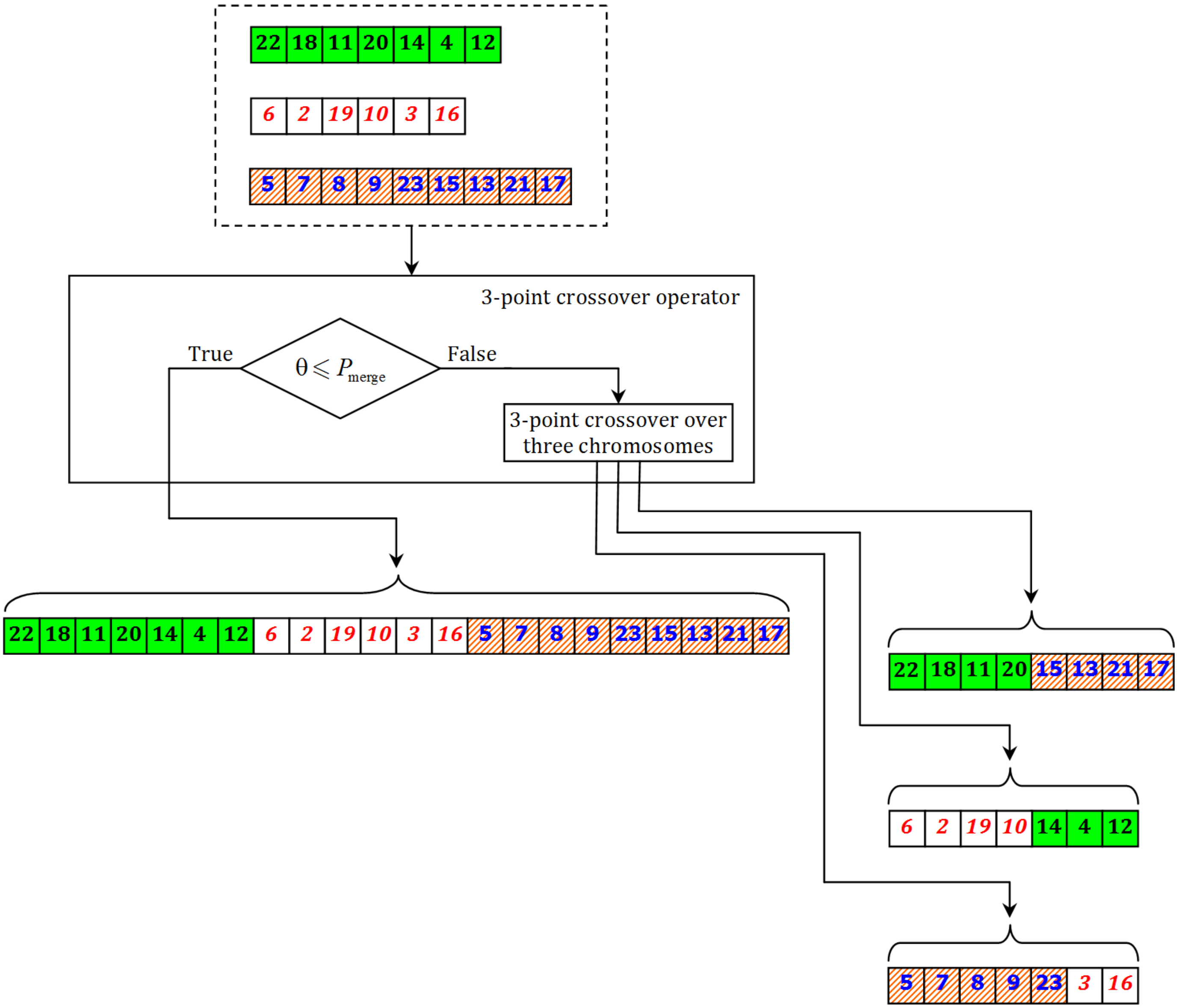

Figure 2. *An example of the 3-point crossover operation over three chromosomes*

only if $M = 3$ (i. e., there are three feeders left before the 3-point crossover operation), so the merged three chromosomes constitute a route of the delivery (apart from the hub). It is easy to see that if $M = 4$ and the 3-point crossover operator merges three chromosomes, then $M = 2$ and further 3-point crossover operations cannot produce a route (35) of a single feeder by the merging. In general, if M (or, before the algorithm starts, $M_{\max}$) is an even number, then the genetic algorithm using only the 3-point crossover operator cannot produce a route of a single feeder.

6. Testing

Denote by $\mu_{2\text{-p}}$ the 2-point crossover operator. This operator is also associated with the corresponding algorithm using it for crossover mutations. Inasmuch as using only the 3-point crossover operator significantly confines the output of the genetic algorithm, we have to test the algorithm using both 2-point and 3-point crossover operators. Denote this algorithm by $\mu_{2,3\text{-p}}$. In fact, algorithm $\mu_{2,3\text{-p}}$ can be thought of as it contains $\mu_{2\text{-p}}$.

Denote by

$$\tilde{\rho}^*_\Sigma\left(\mu_{2\text{-p}}\right) = \tilde{\rho}_\Sigma\left(N, M^*, \{\mathbf{F}_m\}_{m=1}^{M^*}, d_{\max}; \mu_{2\text{-p}}\right) \tag{36}$$

the shortest route length found by $\mu_{2\text{-p}}$ in $I^*\left(\mu_{2\text{-p}}\right)$ iterations. Length (36) is compared to the shortest route length

$$\tilde{\rho}^*_\Sigma\left(\mu_{2,3\text{-p}}\right) = \tilde{\rho}_\Sigma\left(N, M^*, \{\mathbf{F}_m\}_{m=1}^{M^*}, d_{\max}; \mu_{2,3\text{-p}}\right) \tag{37}$$

found by $\mu_{2,3\text{-p}}$ in $I^*\left(\mu_{2,3\text{-p}}\right)$ iterations. The percentage

$$g = 100 \cdot \frac{\tilde{\rho}^{*}_{\Sigma}\left(\mu_{2\text{-p}}\right) - \tilde{\rho}^{*}_{\Sigma}\left(\mu_{2,3\text{-p}}\right)}{\tilde{\rho}^{*}_{\Sigma}\left(\mu_{2\text{-p}}\right)} \quad (38)$$

will show either gain (if positive) or loss (if negative) of using $\mu_{2,3\text{-p}}$ compared to $\mu_{2\text{-p}}$. The percentage

$$g_{\text{iter}} = 100 \cdot \frac{I^{*}\left(\mu_{2\text{-p}}\right) - I^{*}\left(\mu_{2,3\text{-p}}\right)}{I^{*}\left(\mu_{2\text{-p}}\right)} \quad (39)$$

will show either gain (if positive) or loss (if negative) in computational speed of using $\mu_{2,3\text{-p}}$ compared to $\mu_{2\text{-p}}$.

We test both $\mu_{2\text{-p}}$ and $\mu_{2,3\text{-p}}$ for 10 to 150 ports randomly scattered. Positions of all the ports are in matrix (1), which is generated as

$$\mathbf{P} = 50 \cdot \Theta(N, 2) \quad (40)$$

by

$$N = 5 + 5n\,,\ \ n = \overline{1, 29} \quad (41)$$

and an operator Θ(*N*, 2) returning a pseudorandom *N* × 2 matrix whose entries are drawn from the standard uniform distribution on the open interval (0;1). Matrix (40) is identical for both $\mu_{2\text{-p}}$ and $\mu_{2,3\text{-p}}$ in every instance, and we generate 400 such maritime cargo delivery problem instances (i. e., the test is repeated for 400 times) for every *N*. The maximal number of iterations is 8000, whereas the algorithm's early stop condition is used, by which (a run of) the algorithm is stopped if the shortest route length does not change for 400 iterations (a one 20th of the maximal number of iterations). The remaining parameters are:

$$M_{\max} = 16\,,\ \ \lambda = 100\,,\ \ P_{\text{merge}} = 0.15\,, \quad (42)$$

and

$$d_{\max} = \psi\left(\frac{1}{M_{\max}} \cdot \max_{k=1,\,N}\left\{\sum_{j=1}^{N} \rho(k, j)\right\}\right) \quad (43)$$

where function $\psi(x)$ returns the integer part of number *x*.

The comparison of performances of $\mu_{2\text{-p}}$ and $\mu_{2,3\text{-p}}$ is presented in Table 1, where the percentage of violations of the longest possible tour constraint (12) is shown in two separate columns for $\mu_{2\text{-p}}$ and $\mu_{2,3\text{-p}}$, regardless of whether

$$\tilde{\rho}^{*}_{\Sigma}\left(\mu_{2\text{-p}}\right) > \tilde{\rho}^{*}_{\Sigma}\left(\mu_{2,3\text{-p}}\right) \quad (44)$$

or

$$\tilde{\rho}^{*}_{\Sigma}\left(\mu_{2\text{-p}}\right) < \tilde{\rho}^{*}_{\Sigma}\left(\mu_{2,3\text{-p}}\right). \quad (45)$$

The percentage of occurrences of (44), (45) is roughly the same for $\mu_{2\text{-p}}$ and $\mu_{2,3\text{-p}}$. Every instance of 10 to 25 ports has been solved by violating the constraint. This is because the longest possible tour length (43) is relatively too short, and the maritime cargo delivery problem is likely to have no solution by such a constraint. Then, the maritime delivery service will enable one of the few feeders capable of covering longer distances, whereupon the solutions for 10 to 25 ports become feasible. For 30 to 40 ports, more than a half of the respective solutions have been revealed infeasible as well. As previously stated, the infeasibility is rectified by having less "distant" feeders: as the number of ports increases, the minimized number of feeders drops (see Table 2), and therefore the number of feeders that violate the tight constraint drops as well. The maritime cargo delivery problems of 90 ports and more have no infeasible solutions. The number of infeasible solutions for 55 to 85 ports is negligible. Moreover, considering just algorithm $\mu_{2,3\text{-p}}$, there is only 1% of the longest possible tour constraint violations for 55 ports, whereas the $\mu_{2,3\text{-p}}$-solutions to maritime cargo delivery problems of 60 ports and more are all feasible.

The computational speed is also an important property of the algorithm. Measured in the number of iterations taken to achieve a stable route (approximately the shortest length), this metric allows us to determine whether modifying the algorithm speeds up convergence. Table 3 shows the comparison of computational speeds based on (44) and (45) from Table 1, along with percentage (39).

The percentage of the longest possible tour constraint violations shown here similarly to that in Table 1 allows making complete visual comparisons. In general, if gain (38) is positive, i. e., using both the 2-point and 3-point crossover operators shortens the delivery route, algorithm $\mu_{2,3\text{-p}}$ takes up to 10% more iterations to outperform algorithm $\mu_{2\text{-p}}$ (it is over 13% for 70, 75, 90, 100, 110 ports, and it is over 16% for 55 ports). On the contrary, if using both the 2-point and 3-point crossover operators lengthens the delivery route, algorithm $\mu_{2\text{-p}}$ takes roughly between 2% to 8% more iterations to outperform algorithm $\mu_{2,3\text{-p}}$ (it is over 18% for 45 ports, and it is over 10% for 50 ports). Therefore, if we gain in the delivery route length, we may probably lose in computational speed and vice versa. Some exclusions in this test, however, exist. Thus, algorithm $\mu_{2,3\text{-p}}$ outperforms algorithm $\mu_{2\text{-p}}$ both by shortening the route length and decreasing the number of iterations for 10 and 15 ports (where every route is infeasible, though), and for 120 ports. In contrast, algorithm $\mu_{2,3\text{-p}}$ fails to shorten the route length, simultaneously increasing the number of iterations for 30 and 75 ports (where $g_{\text{iter}} < 0$ in both columns).

A typical example of the solution to the maritime cargo delivery problem of 60 ports obtained by algorithm $\mu_{2\text{-p}}$ is shown in Figure 3. Although the algorithm produces the feasible solution after 1475 iterations (not passing even a fifth part of 8000), the tour of one of the four feeders is not perfect-there is an intersection between ports 23, 11 and

43, 60, although the length of the sequence 23, 43, 11, 60 here is obviously shorter. The lengths of the feeders tours are

$$61.8107, 96.2493, 120.7262, 122.0094 \tag{46}$$

(note that these values are rounded). The solution to this problem obtained by algorithm $\mu_{2,3\text{-}p}$ is much better (Figure 4). The algorithm produces the feasible solution after 1879 iterations (by 27.3898 % more that $\mu_{2\text{-}p}$), but the route is

Table 1. *Comparison of performances of $\mu_{2\text{-}p}$ and $\mu_{2,3\text{-}p}$ along with the percentage of violations of the longest possible tour constraint*

		$\tilde{\rho}^*_\Sigma(\mu_{2\text{-}p}) > \tilde{\rho}^*_\Sigma(\mu_{2,3\text{-}p})$				Violations of (12) in $\tilde{\rho}^*_\Sigma(\mu_{2\text{-}p})$	$\tilde{\rho}^*_\Sigma(\mu_{2\text{-}p}) < \tilde{\rho}^*_\Sigma(\mu_{2,3\text{-}p})$				Violations of (12) in $\tilde{\rho}^*_\Sigma(\mu_{2,3\text{-}p})$
		Occurrences, %	$\tilde{\rho}^*_\Sigma(\mu_{2\text{-}p})$	$\tilde{\rho}^*_\Sigma(\mu_{2,3\text{-}p})$	*g*		Occurrences, %	$\tilde{\rho}^*_\Sigma(\mu_{2\text{-}p})$	$\tilde{\rho}^*_\Sigma(\mu_{2,3\text{-}p})$	*g*	
Overall average		47.431	458.1736	439.855	4.1138	%	46.9914	437.4499	455.7348	-4.2375	%
N	10	23	162.5074	154.4293	4.9709	100	11	160.9161	168.1438	-4.4916	100
	15	36.75	245.8067	230.9942	6.026	100	31.25	224.9417	234.6612	-4.3209	100
	20	40	313.768	295.4183	5.8482	100	28.25	330.7839	343.0468	-3.7072	100
	25	51	425.7302	400.6392	5.8937	100	26.5	412.3405	428.5109	-3.9216	100
	30	57	525.7586	503.0035	4.328	98.75	36.25	486.4183	512.1281	-5.2855	98.75
	35	53.5	590.9274	573.517	2.9463	84.5	43.75	540.8242	561.0292	-3.736	84.5
	40	51	583.5659	562.5897	3.5945	59.5	49	544.3362	558.5648	-2.6139	60
	45	52	518.0818	499.4493	3.5964	27.75	48	474.4119	491.0923	-3.516	28.5
	50	52	454.3131	433.8998	4.4932	12.5	48	446.6779	469.3174	-5.0684	10.75
	55	49.75	429.9538	413.2041	3.8957	1	50.25	415.2039	436.668	-5.1695	1
	60	47	426.2364	408.5017	4.1608	0	53	397.0233	421.1186	-6.069	0
	65	47.5	427.1261	407.691	4.5502	0	52.5	402.2233	422.0906	-4.9394	0
	70	50.5	422.2514	404.6076	4.1785	0.25	49.5	405.5613	426.0908	-5.062	0
	75	39	428.1851	404.5786	5.5132	0.25	61	410.862	429.2739	-4.4813	0
	80	47.75	436.9097	421.5664	3.5118	0	52.25	409.9417	431.4875	-5.2558	0
	85	46.75	444.7619	427.6235	3.8534	0.5	53.25	431.4437	448.2362	-3.8922	0
	90	49.75	452.3774	434.3581	3.9832	0	50.25	433.1648	452.6187	-4.4911	0
	95	45.75	455.9687	437.1885	4.1187	0	54.25	435.0251	457.0975	-5.0738	0
	100	55.75	470.2506	448.7076	4.5812	0	44.25	443.5044	462.9149	-4.3766	0
	105	50	468.1526	452.0036	3.4495	0	50	450.2579	470.5579	-4.5085	0
	110	48.75	478.6923	459.2945	4.0523	0	51.25	460.0941	481.9455	-4.7493	0
	115	44	483.7243	470.5481	2.7239	0	56	470.3821	488.3825	-3.8268	0
	120	48.5	494.7954	476.7706	3.6429	0	51.5	475.815	490.2046	-3.0242	0
	125	44.5	507.5657	487.6522	3.9233	0	55.5	483.5862	500.2591	-3.4477	0
	130	53.25	512.0419	493.1712	3.6854	0	46.75	492.2423	512.2915	-4.073	0
	135	41	520.7821	499.6678	4.0543	0	59	501.1695	515.4461	-2.8487	0
	140	60.75	522.946	506.7323	3.1005	0	39.25	503.2026	524.0261	-4.1382	0
	145	37.75	537.827	518.1812	3.6528	0	62.25	515.1312	535.2688	-3.9092	0
	150	51.25	546.0285	529.8046	2.9712	0	48.75	528.5614	543.8372	-2.8901	0

Table 2. *The average number of feeders M * by* $\mu_{2\text{-}p}$ *and* $\mu_{2,3\text{-}p}$

N	10	15	20	25	30	35	40	45	50	55
M^* by $\mu_{2\text{-p}}$	2.42	4.09	5.3875	6.7525	7.5375	7.655	6.98	5.66	4.7	4.1325
M^* by $\mu_{2,3\text{-p}}$	2.32	3.9325	5.275	6.6	7.4975	7.64	6.9175	5.64	4.6925	4.1775
N	60	65	70	75	80	85	90	95	100	105
M^* by $\mu_{2\text{-p}}$	3.6325	3.5225	3.16	3.045	3.0175	2.9725	2.96	2.775	2.6925	2.4025
M^* by $\mu_{2,3\text{-p}}$	3.74	3.44	3.19	3.045	3.0025	2.995	2.9475	2.8125	2.62	2.42
N	110	115	120	125	130	135	140	145	150	
M^* by $\mu_{2\text{-p}}$	2.305	2.1375	2.095	2.0325	2	2.0225	2	2	2	
M^* by $\mu_{2,3\text{-p}}$	2.3425	2.18	2.07	2.0525	2	2.02	2	2.025	2	

5.1186 % shorter. Besides, the shorter route consists of three feeders whose tour lengths are

$$120.2504,\ 132.2812,\ \text{and}\ 127.7488 \tag{47}$$

being roughly equal and not much longer than the longest tour in (46). This means that the maritime delivery service, apart from the shorter route in Figure 4, spares here a feeder. Moreover, the lengths of the four feeders tours (46) are more unequal than the lengths (47). This additionally rationalizes the occupation of the three feeders.

As the longest possible tour constraint (12) is made looser, i. e. the longest possible tour length becomes not so short, the percentage of violations of constraint (12) in both $\mu_{2\text{-p}}$ and $\mu_{2,3\text{-p}}$ becomes significantly lower even for a few tens of ports. Thus, if

$$d_{\max} = \psi\left(\frac{3}{M_{\max}} \cdot \max_{k=1,N}\left\{\sum_{j=1}^{N} \rho(k,j)\right\}\right) \tag{48}$$

instead of (43), then this violation rate is about 50 % for 15 ports, but it is 0 for 20 ports or more. The percentage of occurrences of (44), (45) is still roughly the same for $\mu_{2\text{-p}}$ and $\mu_{2,3\text{-p}}$, although the occurrence of (44) is a little bit more probable (just it is in Table 1). The violation rate by (48) for 10 ports is less than 100%, but it is not less than 90 %. If

$$d_{\max} = \psi\left(\frac{6}{M_{\max}} \cdot \max_{k=1,N}\left\{\sum_{j=1}^{N} \rho(k,j)\right\}\right) \tag{49}$$

then there are almost no violations for 15 and 10 ports. Furthermore, it is much more probable at (49) that the gain by (38) will appear positive.

Consequently, half of routes could be made shorter while the 2-point crossover operator is solely used. On the contrary, half of routes could also be made shorter while both the 2-point and 3-point crossover operators are solely used (embedded in the corresponding algorithm $\mu_{2,3\text{-p}}$). The best decision here is to run both $\mu_{2\text{-p}}$ and $\mu_{2,3\text{-p}}$ simultaneously (in parallel), whereupon the shortest route length is

$$\tilde{\rho}_{\Sigma}^{**} = \min\left\{\tilde{\rho}_{\Sigma}^{*}\left(\mu_{2\text{-p}}\right), \tilde{\rho}_{\Sigma}^{*}\left(\mu_{2,3\text{-p}}\right)\right\} \tag{50}$$

and the respective route is selected according to (50).

7. Discussion of the Contribution

Our contribution to the field of genetic algorithms consists in the suggested 3-point crossover operation over three chromosomes followed by a confluence with 2-point crossover mutations and a two-branched algorithm to obtain the shortest route length (50). This two-branched algorithm does not have practical limitations unless the maximal number of available feeders is 2. The practical applicability and significance of the suggested crossover mutation operation (involving both 2-point and 3-point crossover mutations) can be illustrated by an example generated for 15 ports by (49) implying a looser longest possible tour constraint (Figure 5). The longest possible tour length is 186. The route by $\mu_{2\text{-p}}$ whose length is $\tilde{\rho}_{\Sigma}^{*}(\mu_{2\text{-p}}) = 211.6745$ consists of two feeders tours whose lengths are 135.2037 and 76.4708. The route by $\mu_{2,3\text{-p}}$ whose length is $\tilde{\rho}_{\Sigma}^{*}(\mu_{2\text{-p}}) = 183.4649$ consists of a single feeder tour. Therefore, the maritime delivery service, apart from the 15.376 % shorter route, spares here a feeder. It is noteworthy that these results are obtained by $I^*(\mu_{2\text{-p}}) = 482$ and $I^*(\mu_{2,3\text{-p}}) = 454$ (by the maximum of 8000 iterations and the early stop condition of 400 iterations). Amazingly enough, the same results are obtained by setting the maximum at 800 iterations and the early stop condition at 40 iterations, where $I^*(\mu_{2\text{-p}}) = 122$ and $I^*(\mu_{2,3\text{-p}}) = 94$ (the difference between the past iterations is the same). The gains in Table 1 are noticeably less than the gain in this example, but Table 1 shows the results of the worst-case scenario when the longest possible tour constraint (12) is very tight, as given by (43). It is expected

Table 3. *Computational speed of* $\mu_{2\text{-}p}$ *and* $\mu_{2,3\text{-}p}$ *compared by Table 1*

		$\tilde{\rho}^*_\Sigma(\mu_{2\text{-}p}) > \tilde{\rho}^*_\Sigma(\mu_{2,3\text{-}p})$			**Violations of (12) in $\tilde{\rho}^*_\Sigma(\mu_{2\text{-}p})$**	$\tilde{\rho}^*_\Sigma(\mu_{2\text{-}p}) < \tilde{\rho}^*_\Sigma(\mu_{2,3\text{-}p})$			**Violations of (12) in $\tilde{\rho}^*_\Sigma(\mu_{2,3\text{-}p})$**
		$I^*(\mu_{2\text{-}p})$	$I^*(\mu_{2,3\text{-}p})$	g_{iter}		$I^*(\mu_{2\text{-}p})$	$I^*(\mu_{2,3\text{-}p})$	g_{iter}	
Overall average		2697.546	2901.208	-7.4452	%	2946.626	2770.845	5.3356	%
N	**10**	**455.3043**	**445.75**	**2.0985**	100	**448.8182**	**429.6591**	**4.2688**	100
	15	**504.2177**	**469.034**	**6.9779**	100	**514.432**	**465.312**	**9.5484**	100
	20	559.3563	578.4125	-3.4068	100	559.928	534.736	4.4991	100
	25	654.0049	693.3627	-6.018	100	667.056	664.92	0.3202	100
	30	819.2763	869.0132	-6.0708	98.75	864.2414	995.4828	-15.1857	98.75
	35	1065.969	1195.921	-12.1909	84.5	1134.354	1105.817	2.5157	84.5
	40	1376.004	1440.702	-4.7018	59.5	1524.194	1395.393	8.4504	60
	45	1510.132	1677.746	-11.0993	27.75	1888.138	1544	18.2263	28.5
	50	1761.965	1827.675	-3.7294	12.5	2134.174	1920.245	10.024	10.75
	55	1812.197	2113.233	-16.6116	1	2122.134	2007.119	5.4198	1
	60	1853.048	2064.561	-11.4143	0	2367.212	2183.637	7.7549	0
	65	2181.851	2410.127	-10.4625	0	2461.028	2287.552	7.0489	0
	70	2224.693	2532.825	-13.8505	0.25	2658.274	2461.274	7.4108	0
	75	2284.838	2598.961	-13.7481	0.25	2659.676	2739.721	-3.0096	0
	80	2653.943	2814.316	-6.0428	0	2894.164	2685.094	7.2238	0
	85	2722.597	3006.794	-10.4385	0.5	3114.459	2952.709	5.1935	0
	90	2883.697	3291	-14.1243	0	3146.791	3064.135	2.6267	0
	95	2996.233	3324.325	-10.9502	0	3447.094	3312.103	3.9161	0
	100	3335.43	3772.412	-13.1012	0	3647.566	3520.439	3.4853	0
	105	3648.702	3968.754	-8.7717	0	3831.799	3558.123	7.1422	0
	110	3652.281	4178.803	-14.4163	0	4032.844	4017.762	0.374	0
	115	4049.925	4203.404	-3.7897	0	4182.348	3811.094	8.8767	0
	120	**4269.557**	**4251.351**	**0.4264**	0	**4543.357**	**4164.734**	**8.3336**	0
	125	4130.184	4443.36	-7.5826	0	4535.119	4336.525	4.379	0
	130	4586.281	4767.798	-3.9578	0	4677.566	4284.959	8.3934	0
	135	4792.899	4928.614	-2.8316	0	4870.484	4669.73	4.1219	0
	140	4957.222	5220.527	-5.3115	0	5216.717	4776.971	8.4296	0
	145	5090.86	5475.712	-7.5597	0	5583.249	5081.49	8.9869	0
	150	5396.156	5570.547	-3.2318	0	5724.94	5383.783	5.9591	0

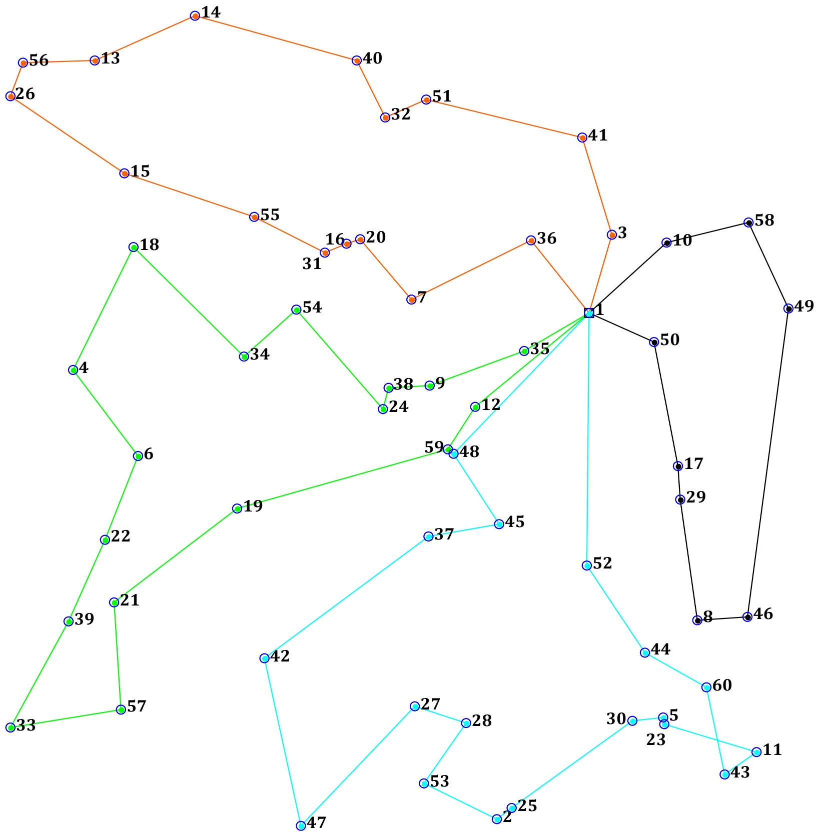

Figure 3. *The solution of an instance with 60 ports by* $\mu_{2\text{-}p}$, *where four feeders are used and* $\tilde{\rho}^*_\Sigma = 400.7957$

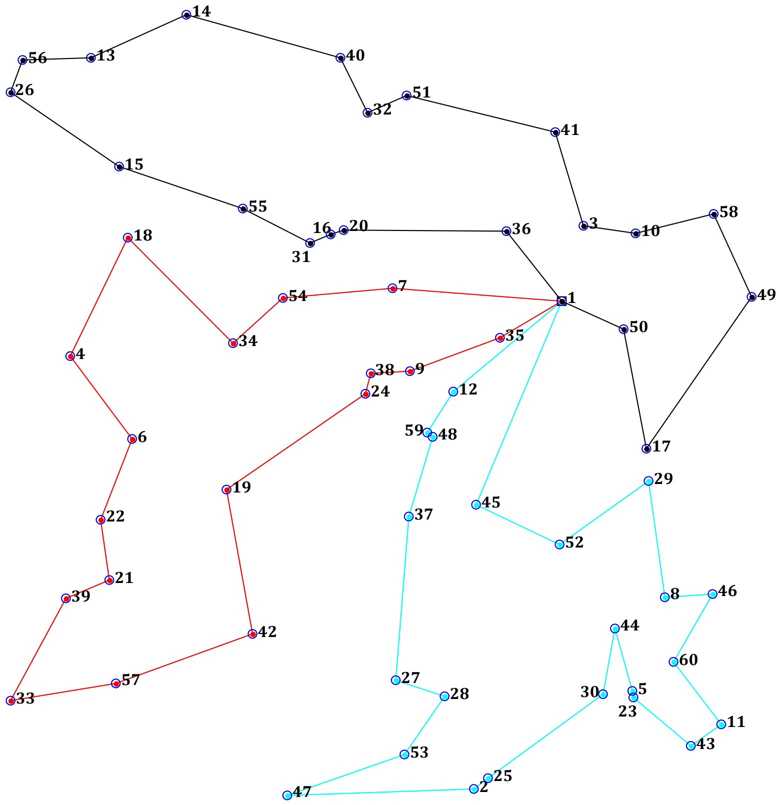

Figure 4. *A better solution of the instance with 60 ports in Figure 3 by* $\mu_{2,3\text{-}p}$, *where three feeders are used and* $\tilde{\rho}^*_\Sigma = 380.2804$

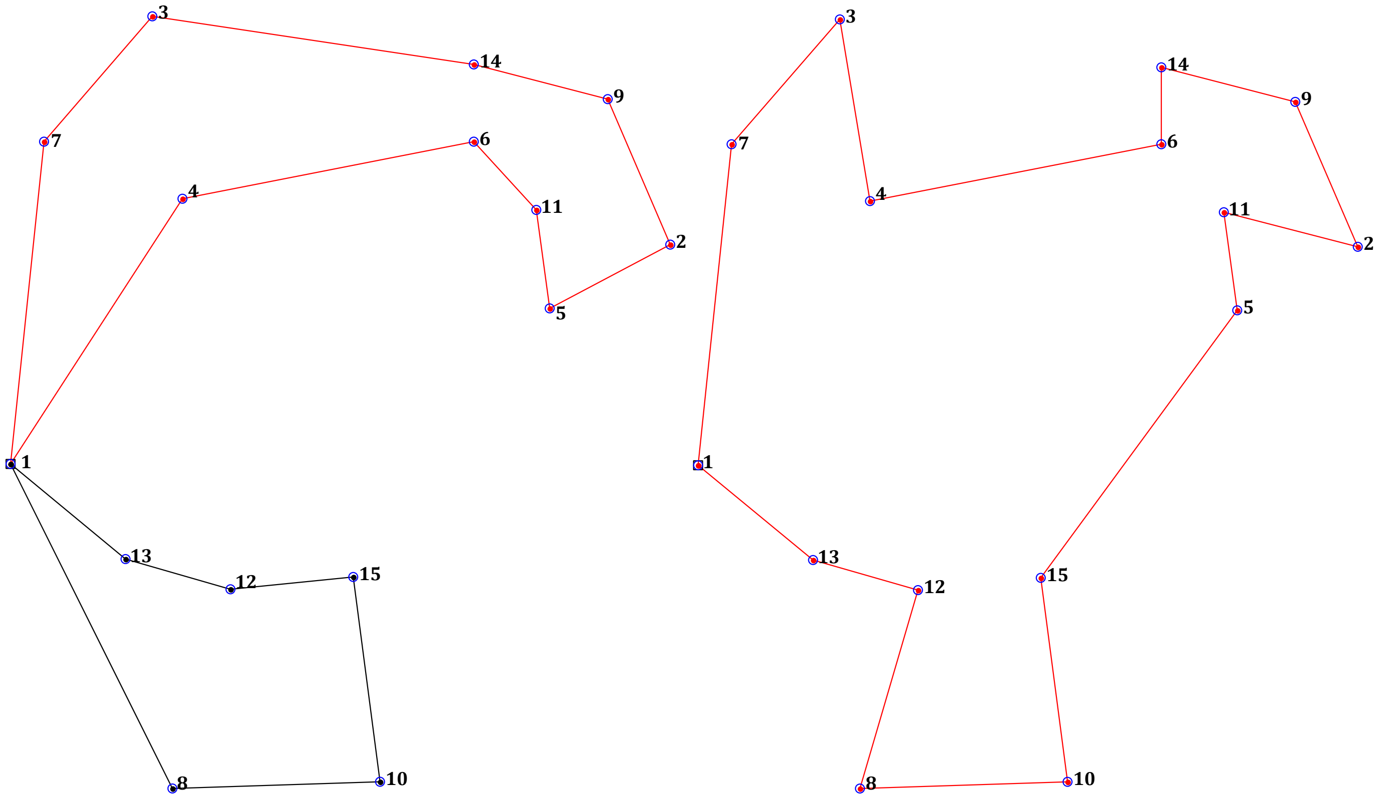

Figure 5. *The route by* μ_{2-p} *(left) shortened by 15.376 % by using* $\mu_{2,3-p}$ *(the route at the right)*

that the gain can be very significant if the constraint is looser, whether there are 10 ports or a few tens and more.

Along with minimizing the route length, the algorithm runs with the effect of the indirect minimization of the number of feeders. This is another side of maritime cargo delivery optimization, as maintenance of the feeder fleet is much more expensive. If the route consists of one or a few too-short feeders tours, then some tours may be accomplished by the same feeder (while some other feeder is accomplishing its longer tour), but this decision is made only by the maritime delivery service.

It is necessary to mention that, despite our model of delivering cargo is very simple, it reflects the delivery core-distance and capacity (capability). We also based our research on the fact that the positions of the ports are generated normally. This might be a tiny bias because, in reality, a maritime delivery service may be contracted to deliver from its hub to neighboring and distant ports that, in the aggregate, would not look like the center-based cluster shown in Figure 3 (Figure 4). However, we believe that this drawback is counterbalanced by our worst-case scenario consideration.

Another seeming deterrent is the computational speed that has been not improved. Indeed, algorithm $\mu_{2,3-p}$ does not converge faster. Nevertheless, running both algorithms μ_{2-p} and $\mu_{2,3-p}$ in parallel is strongly recommended (and it is perfectly possible using methods of parallelization of computing). Consequently, with paying attention back to Table 3, the computational speed herein is not slowed down.

8. Conclusion

We have presented a 3-point crossover operator to the genetic algorithm for solving a maritime cargo delivery problem formulated as a multiple traveling salesman problem. This operator returns slightly more complex crossover mutations, which in the confluence with 2-point crossover mutations shorten the delivery route in about 50% of algorithm runs. However, this 2-point-and-3-point crossover algorithm does not shorten every route. To definitely increase the genetic algorithm performance, we have proposed to run both the 2-point crossover algorithm and the 2-point-and-3-point crossover algorithm in parallel and select the minimal length route. The route may be shortened by a few percentage points, but the resulting cost savings for maritime cargo delivery are substantial.

Therefore, it is a significant contribution to the field of genetic algorithms, which are specifically used to optimize maritime cargo delivery. The impact of our contribution is obvious for policymakers and practitioners: the rationalization of maritime transportation route planning saves energy (fuel for ship feeders is saved), transport (feeders themselves are spared), and human (fewer seamen and service personnel are needed) resources.

Potential development of the research would be to test more complex mutations, including combinations of flip, swap, and slide, in addition to "pure" crossover [18]. We believe that complicated mutations may be acceptable if the mutated part of the chromosome is relatively small (i. e., the mutated chromosome is still "recognizable" compared to its parents). The question of how the mutation diversity influences algorithm convergence and the indirect minimization of the number of feeders is still open. Reducing this number and the equalization of the lengths of feeders tours do lead to an additional reduction in the cost of maritime cargo delivery.

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Concept design: M.O. Malaksiano, Data Collection or Processing: A.Y. Romanov, Analysis or Interpretation: V.V. Romanuke, Literature Review: A.Y. Romanov, M.O. Malaksiano, Writing, Reviewing and Editing: V.V. Romanuke.

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Fleet Optimization in Ro-Ro Transportation: A Case Study from Türkiye

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Abstract

Although maritime transport is the cheapest transportation mode, the management of ships is very costly. Ship management companies try to get the minimum cost and highest profit using ships effectively and efficiently. Therefore, they need to carry out shipment planning at the optimum level. The purpose of this research is to perform the optimum shipment planning of six ships in different sizes and capacities in a Ro-Ro fleet belonging to a ship management company operating in the Black Sea Region. On the basis of data obtained from the company that had problems in operating ships in its fleet effectively and efficiently, a model in A Mathematical Programming Language has been created, and this model has been solved with the GNU Linear Programming Kit, a mixed-integer program solver. Shipment planning has been conducted within the framework of six ships and a 1-year planning horizon, and profit maximization has been determined as the objective function.

Keywords: Fleet planning, Optimization, Maritime, Ro-Ro transportation, Maritime management

1. Introduction

The activities undertaken to accomplish the voyage of vessels within their bodies from one port to another port or from one location to another may be defined as the vessel operation in marine transportation. The criteria for a successful vessel operation are to maintain the idle time of ships in a fleet to a minimum by maximizing the efficiency of the fleet and reducing long-term expenditures regularly. Accordingly, neither fleet planning nor vessel operation should be separated during the planning of fleets. The knowledge of all expenditures is necessary for an effective fleet planning. In the long run, expenditures that are not fully addressed will result in a rise in costs and a decline in profitability [1].

The fleet size of vessel operators may change over time, and a fleet may include vessels of various types, vessels of different sizes, vessels with different cost structures, and diverse vessels with specific features. While the size of a fleet and the variety of transport operators might significantly differ, the shared objective of vessel operators is to optimize their fleet (fixed or variable) [2].

The main field of activity of vessel operation is fleet management. Vessel management activities and fleet management are performed together with the main lines. Fleet management necessitates collaboration with other divisions within the enterprise and the development of various strategies to achieve shared objectives. As a consequence of this necessity, a critical issue known as "fleet planning" appears. The goal of fleet planning is to ensure that the fleet under management gets intended results considering market conditions and revenue levels [3]. Some factors that affect the decision making process in fleet planning are presented as follows [3,4]:

- Large vessels may save money by taking advantage of economies of scale; however, this can pose problems for very large vessels while docking at ports.

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*This study is produced from the Selçuk Kahveci's doctoral thesis.

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- The operational flexibility of smaller vessels is better than that of bigger vessels. This flexibility provides advantages in docking at ports and finding cargoes.
- The expansion of the container market drives vessels to grow in size and voyage frequency to increase.
- It is also easy to manage vessels that are built in the same class and with the same features.
- Expedition timetables should be organized in line with the capabilities of the managed fleet.
- Fleet requirements should be planned according to high, medium, or low market demands.

In general, vessel operators benefit from their past experience while making decisions. Apart from the fact that making decisions based on experience rather than analytical approaches is simpler for businesses with a limited number of vessels in their fleets, fleet planning exposes far more complex factors as the number of vessels and lines grows. Consequently, more challenging problems arise [5].

Complex operational challenges develop with the assignment of cargoes to a suitable vessel that meets all constraints, particularly in cargo-related activities and cargo operations. The constraints that must be satisfied may be listed, such as the load schedule, load capacity of vessels, and if destination ports are appropriate for the draft and length of vessels. Except for major regular line freight carriers, a small number of medium-sized businesses employ support systems for optimization-based analytical decisions [6].

During demand shrinkage, fleet managers of maritime transport corporations must decide which vessels to maintain in operation and which vessels to retire due to overcapacity [7]. In general, managers gain from their own personal experiences while making decisions. Although enterprises with a limited number of fleets can easily make decisions based on experience without utilizing analytical approaches, as the number of vessels and lines grows, fleet planning gets more complicated, making it more difficult to resolve challenges [5].

Based on the literature review, several researchers have focused on different aspects of fleet planning-related problems. Xinlian et al. [8] employed a dynamic programming model to deploy eight kinds of vessels on six transport lines in search for an optimal fleet plan and for decision making in maritime businesses. The annual load capacity of vessels for each line, annual operating expenditures, lay-up costs, purchase costs of vessels intended to join the fleet, and scrap values of vessels that will leave the fleet if required were the variables and parameters utilized in the cost minimization model. Karaoğlan [9] employed optimization techniques to examine the vessels of a maritime corporation in an application study on tanker scheduling. The study shows that how vessels might be scheduled and profit could be maximized under an optimal fleet plan. Fagerholt et al. [10] intended to distribute the most appropriate voyages to existing vessels in the fleet and to set vessel routes and timetables in a manner that minimizes costs or maximizes revenues in their research on the fleet distribution problem. Meng and Wang [11] addressed a short-term Liner Ship Fleet Planning problem with cargo shipment demand uncertainty for a single-liner container shipping company in their study related to the programming model with chance constraints for the short-term Liner Ship Fleet Planning problems. Gelareh and Meng [12] produced a mixed-integer non-linear programming model for scheduled shipping operations under the short-term fleet planning in marine transportation and solved it by transforming it into an integer linear programming model via the CPLEX solver. Meng et al. [13] sought optimum solutions to a short-term fleet planning problem through the stochastic integer linear programming method. Branchini [14] addressed the tactical planning problem that many liner shipping corporations suffer when they attempt to introduce optional spot voyages in the medium term to generate income. The optimization problem that has been developed for profit maximization was formulated as a mixed-integer programming model that was defined on a directed graph node, which represented the contract and spot voyages. Çakalöz [15] analyzed Ro-Ro transportation in Türkiye and determined how optimum fleet planning could be accomplished. All Ro-Ro lines were analyzed in the context of fleet optimization of vessels, which were the subject of Turkish international trade. Fancello et al. [16] studied the fleet vessel scheduling problem in a Ro-Ro ship fleet. They indicated that this issue is frequently being addressed among existing marine businesses. They identified the problem as a response to the need to improve basic transport services for the development of the island and surrounding areas by re-planning existing connections to improve the overall performance of the Tyrrhenian maritime network. In their study, Ma et al. [17] developed a ship routing and speed optimization model that can minimize transportation costs and emissions while taking Emission Control Area regulations into account. Compared to a real-life scenario, the model can reduce the total costs and emissions of a ship and limit the effect of the increase in the total cost caused by fuel prices. The model can also provide different optimal routes and speeds for different emission levels. In the study aimed at profit maximization, Pasha et al. [18] proposed an optimization model in which tactical liner shipping decisions are handled and emission values are considered. In their study, a heterogeneous fleet of ships created for each route was deployed. They presented a decomposition-based heuristic algorithm to solve the proposed model, which can efficiently handle large-sized problem instances. Numerical experiments have been presented on real-life scenarios that show the effectiveness of the proposed methodology. Škurić et al. [19] investigated the organization of transportation policies, which provides regular passenger ferry fleet services between a given set of routes and predetermined passenger preferences within a defined planning horizon. The proposed mixed-integer linear programming formulation was deployed for a deterministic optimization problem related to maximizing the ferry operator's profit. As a result of the three different mathematical models they employed, equal or better high-quality solutions have been obtained in less computation time compared to the current situation.

In the present study, we present a maritime business that operates in the Samsun Province of the Black Sea Region and specializes in Ro-Ro marine transportation. The objective is to provide an efficient fleet utilization plan/scheme for this maritime business to allow them to boost its profitability by operating its fleet efficiently and effectively. The study intends to ascertain the fact that vessels are not operated efficiently and effectively, to offer a good fleet planning under certain assumptions, and to investigate and plan what the optimum fleet size might be.

2. Context and Problem Formulation

With the dissolution of the Union of Soviet Socialist Republics, Ro-Ro transportation in the Black Sea Region began to rise. This has been facilitated by the mutually growing trade volume and bilateral agreements. Particularly, the substantial export of citrus products from Türkiye resulted in an important Ro-Ro traffic. In this study, a local maritime business that provides Ro-Ro transportation service in the Black Sea was addressed. By their request, the identity of the business is not disclosed, and necessary discretion is respected in this study. The data for the study were obtained through face-to-face interviews with the accounting and leasing departments of the business. The model constructed in this study was developed for the operational plan of six Ro-Ro vessels that operate in Samsun Port in the Black Sea.

The interviews with corporate executives indicate that the fleet was not being operated properly and efficiently, and as a consequence, the business' yearly revenue was lower than it should have been. As corporate data have not been held in a database management system environment, gathering, organizing, and structuring data have been a challenge during the preparation stage before problem formulation. Data tables have been created in the Microsoft Excel© program with the data obtained from the accounting and charter departments of the business. The age of the vessels, fuel consumption, capacity, daily operating expenses, charter rates, yearly charter statistics, depreciation information, port holding charges, and cargo transportation figures for 2018, as well as the gathered revenue data, such as the number of vehicles they transported between 2014 and 2018, were organized and structured within the data tables. With these data tables, examining and analyzing generated income and incurred expenses were enabled.

From Samsun to Russia, the business mostly carries citrus, vegetables, and fruits. As these transports are seasonal, it intensifies at certain times of the year. Citrus transportation is particularly concentrated between mid-October and mid-January. The vessels operate at almost full capacity during this three-month period, whereas some of the vessels are chartered. Those that are not chartered are docked at the port during the other months. According to the data acquired from the business, the vessels in the fleet were largely chartered throughout the Mediterranean and Black Sea regions during the past two years. The majority of vessel charter demands originate from ports in the Arabian Gulf and Mediterranean. Charterers often charter vessels for a limited length of time, and the busy three-month period of the business hinders them from doing so. As a result, the operator encounters challenges in the operation of its vessels in the next nine months and is unable to maximize profit from the vessels. The lack of fleet planning for vessels throughout the year is one of the primary causes of these challenges (Table 1).

Figure 1 indicates the number of vehicles carried from Samsun Port by the vessels of the business that have been studied from 2014 to 2018 and the ratio of total vehicles transported from Samsun Port. While the rate of vehicles transported by the vessels of the business that has been

Table 1. *Number of vehicles carried by ships departing Samsun Port between 2014 and 2018*

Years	i1	i2	i3	i4	i5	i6	Total
2014	483	904	1981	1467	2468	2150	9453
2015	1620	2186	858	2564	1990	910	10128
2016	324	1440	1607	594	379	1013	5357
2017	1490	1831	2800	2083	768	1023	9995
2018	1115	1956	1559	1857	208	651	7346
Total	**5032**	**8317**	**8805**	**8565**	**5813**	**5747**	**42279**

included in the study was over 35% in 2017, this rate dropped to 21% in 2018.

Vessels are chartered for various lengths of time, ranging from one week to five months. The lack of any planning impedes vessels from operating effectively and efficiently. While the average daily operating cost of the container vessel in the fleet is 1700 USD, the average daily operating costs of other Ro-Ro vessels range from 1900 to 2200 USD. Except during the peak months of October and January when the business is occupied, an average operating cost of 1400 USD is incurred per day while the vessels are not operated and are docked. Meanwhile, the daily time-based charter (T/C) charges of vessels range from 4200 USD to 4750 USD (Table 2).

The navigation time of the vessels was computed based on the speed data received, and the navigation times were found to be 21 h for the i1 and i2 vessels and 19 h for the other vessels. As the assignment plans of the vessels are reviewed on a weekly basis, periods other than the cruise time were estimated, such as port times, waiting, and congestion. Port times vary depending on the capacities of the vessels. These times were determined as 35 h for i1 and i2 vessels, 32 h for i3 and i4 vessels, and 30 h for i5 and i6 vessels. Furthermore, once the vessels have finished loading or unloading, they are assumed to begin sailing immediately.

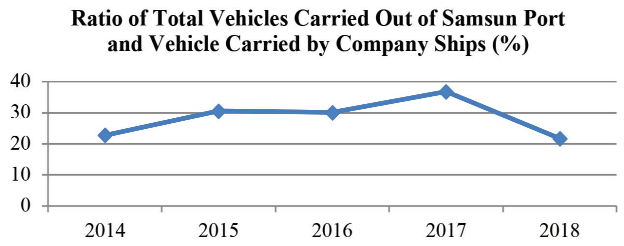

Figure 1. *Vehicle transportation rate of company ships and all ships leaving Samsun Port [20]*

The weekly fuel costs of the vessels were calculated based on this data.

2.1. Mathematical Modeling

In addition to reviewing past studies from various sources, the corporate personnel and expert perspectives in the industry were examined. The mathematical model that was constructed in this study is a mixed-integer linear programming model, which aims profit maximization. The dataset included information on the operating and voyage costs of the vessels and some information derived from their technical features, the revenues generated by their voyages in 2018, and 2018 fuel prices.

After carefully examining this maritime business operation model, we conclude that the business faces the major challenge of not being able to operate its fleet efficiently, rather than a network optimization problem, such as routing. Adopting effective fleet planning to ensure that the business can allocate vessels in its fleet to its own operations or to the charter market through chartering seems to be the only solution for the business to utilize its resources most effectively and optimize its operational profit.

Given the condition of the business, three distinct categories of decision variables have appeared to be basically eligible for the mathematical model to be constructed for fleet planning. The first is whether the relevant vessel would be deployed in its own operations in the corresponding week. The second is whether the relevant vessel would be chartered in the corresponding week. The third is if the relevant vessel would be dispatched to the shipyard. Due to the nature of the decision variables, the constructed model appears as a binary mathematical program. The constructed maximization model intends to maximize the overall operational profit by adding the profit generated by the business from its operations and the profit from the charter market.

Table 2. *Features of ships and operating costs (USD)*

Features of ships and operating costs	i1	i2	i3	i4	i5	i6
Truck/semi-trailer/trailer capacity	81	81	66	66	54	54
Insurance ($/year)	40.000	40.000	35.000	35.000	30.000	30.000
Stores ($/year)	71.000	71.000	70.000	70.000	70.000	70.000
Depreciation ($/year)	177.600	177.600	133.200	133.200	111.000	111.000
Personnel ($/year)	379.400	379.400	361.800	361.800	357.500	357.500
Repair-maintenance-attitude ($/year)	135.000	135.000	130.000	130.000	125.000	125.000
Running cost ($/daily)	2.200	2.200	2.000	2.000	1.900	1.900
Speed (knot/hour)	10	10	11	11	11	11
Cruising fuel consumption (ton/hour)	0.45	0.45	0.45	0.45	0.4	0.4
Fuel consumption in the port (ton/hour)	0.04	0.04	0.03	0.03	0.03	0.03
Financial value of ships $	3.200.000	3.200.000	2.400.000	2.400.000	2.000.000	2.000.000

The model to be constructed is based on the following assumptions:

1) The planning horizon is one year and is on a weekly basis. It is assumed to work for 52 weeks in a year. Therefore, a discrete optimization model will emerge.

2) The business only has one port from which to operate. To put it another way, there are no other problems, such as routing.

3) A vessel is either allocated by the business for its operations, on charter, or dispatched to the shipyard for other activities, such as maintenance and repair, in a given week.

4) When a vessel is allocated by the business for its operations, it is ready to be assigned to the operation again for the following week, chartered, or dispatched to the shipyard for maintenance and repair, among others.

5) When a vessel is intended to be chartered in the charter market, it can be chartered immediately.

6) Once a vessel is chartered, it remains on the charter for at least four consecutive weeks.

7) Vessels operate at full capacity when assigned to the operations of the business.

8) In cases where vessels are dispatched to a shipyard for other operations, such as maintenance and repair, they need two weeks every year for these operations, which must be set sequentially.

9) Although the periodic maintenance-epair operations of the vessels are carried out at certain periods because the established model covers a period of one year without continuity, it is sent for maintenance in any week in the relevant year, covering a period of two weeks in a row.

10) It is obligatory for a vessel to be assigned to its own operations with the capacity to satisfy at least the weekly load demand of the business.

The following would be the information that will be achieved after the model is solved under the above assumptions:

1) In which weeks may the business deploy which vessel for its own operations,

2) In which weeks may the business charter which vessel,

3) In which weeks will the business dispatch its vessels for other operations, such as maintenance and repair,

4) The maximum profit to be generated from the fleet optimization.

The following is the notation for the constructed mathematical model and the associated variable and parameter definitions:

- i∈ I: set of ships
- t∈ T: set of weeks
- x_{it}∈ {0, 1} binary decision variable representing the decision whether the ship "i" should be utilized by the company at week "t" for its own operations
- y_{it}∈ {0, 1} binary decision variable representing the decision whether the ship "i" should be charter at week "t"
- z_{it}∈ {0, 1} binary decision variable representing the decision whether the ship "i" should be send to shipyard week "t"

The parameters of the model are given below:

- Ҡ_i: capacity of ship "i"
- λ_t: load of the company at week "t"
- r^{o}_{it}: operational revenue of ship "i" being deployed at the company's own operations at week "t"
- c^{o}_{it}: operational cost of ship "i" being deployed at the company's own operations at week "t"
- c^{L}_{it}: maintenance–repair cost of ship "i" for sending it to the shipyard week "t"
- r^{R}_{it}: charter revenue of ship "i" for charter at week "t"
- c^{R}_{it}: charter cost of ship "i" for charter at week "t"
- s_t: total idle capacity in week "t"
- μ: penalty coefficient for unit idle capacity.

Finally, the mixed-integer model can be written as follows:

$$Z\,max=\sum_{i=1}^{m}\ \sum_{t=1}^{n}\left(x_{it}\left(r^{o}_{it}-c^{o}_{it}\right)+y_{it}\left(r^{R}_{it}-c^{R}_{it}\right)-z_{it}c^{L}_{it}\right)-\mu\sum_{t=1}^{n}s_t$$

$$s.t$$

$$\sum_{i=1}^{m}x_{it}\text{Ҡ}_i-\lambda_t-s_t = 0\ ;\forall t\in T \tag{1}$$

$$x_{it}+y_{it}+z_{it} = 1;i = 1,\ldots,m;t = 1,\ldots,n \tag{2}$$

$$\left(1-y_{i(t-1)}\right)+y_{it}+\left(1-y_{i(t+1)}\right) \leq 2;i = 1,\ldots,m;t = 2,\ldots,n-1 \tag{3}$$

$$\left(1-y_{i(t-1)}\right)+y_{it}+y_{i(t+1)}+\left(1-y_{i(t+2)}\right) \leq 3;i = 1,\ldots,m;\ t = 2,\ldots,n-2 \tag{4}$$

$$\left(1-y_{i(t-1)}\right)+y_{it}+y_{i(t+1)}+y_{i(t+2)}+\left(1-y_{i(t+3)}\right) \leq 4;i = 1,\ldots,m;\ t = 2,\ldots,n-3 \tag{5}$$

$$\sum_{i=1}^{n}z_{it} = 2\ ;\forall i\in I \tag{6}$$

$$\left(1-z_{i(t-1)}\right)+z_{it}+\left(1-z_{i(t+1)}\right) \leq 2;i = 1,\ldots,m;t = 2,\ldots,n-1 \tag{7}$$

$$x_{it}\in\{0,1\};y_{it}\in\{0,1\};z_{it}\in\{0,1\};\ s_t \geq 0;\forall i\in I;\forall t\in T$$

The objective function of this model is to maximize the profit of the this maritime business by assigning its fleet between their own operations and chartering while respecting the necessity of maintenance by sending to the shipyard. At the same time, another part of this multi-objective model comes from minimizing the idle capacity assigned to operations.

The following are the constraints that will be imposed on the model:

The first constraint stipulates that the total capacities of the vessels allocated by the business for its own operations during the planning week must be greater than or equal to the volume of cargoes that the business must transport. Here the constraint is written as equality with a surplus variable (1).

The second constraint stipulates that a vessel is either allocated by the business for its operations, on charter, or dispatched to the shipyard for other activities, such as maintenance and repair, in a given week (2).

The third, fourth, and fifth constraints provide that certain patterns are imposed on the model by preventing such patterns in order for a vessel to be chartered for at least four consecutive weeks (3), (4), (5).

The sixth constraint stipulates that a vessel should be dispatched to the shipyard for maintenance-repair operations for a total of two weeks per year during the planning year (6).

Similar to constraints (3), (4), and (5), the seventh constraint is the prohibition of a certain pattern in order for the two-week time period allocated to the shipyard in constraint (6) to remain consecutive (7).

To construct a computer model of the above algebraic model, one of the several algebraic modeling systems available today should be employed. Hence, we have preferred the GNU MathProg language (GMPL), which is an open-source/free implementation of A Mathematical Programming Language (AMPL), which comes with the GNU Linear Programming Kit (GLPK) solver.

The AMPL modeling system allows us to express constrained optimization problems in an algebraic representation that is close to that utilized in conventional mathematics. The AMPL's solve command causes the AMPL to instantiate the current problem, send it to a solver, and attempt to read a solution computed by the solver [21].

The GLPK comes with its own modeling language, the GMPL, a subset of the AMPL. It contains structures that allow modelers to easily express a wide range of mathematical programming conditions. Furthermore, the GLPK includes several examples that offer a solid overview of how to formulate optimization problems in GNU MathProg. The GLPK may be used as a library or GLPSOL, a standalone solvent. This solver is capable of reading widely accepted file formats, such as mps and cplex-lp. In addition, by constructing the model in GNU MathProg and delivering the model and data files with the mod and dat extensions directly to the GLPK solver, the modeling and solving processes may be accomplished sequentially. While the GLPK solver can be run from the command line in all common operating systems, there is also GUSEK, also known as an integrated development environment with a graphical user interface that was developed for Windows [22].

3. Findings

3.1. Solution of the Mathematical Model

The model was constructed using GMPL (GNU Mathprog), an open-source/free version implementation of the AMPL, and solved with a laptop with a GLPK integer optimizer v4.65 linear and integer program solver, having an AMD® Ryzen 5 3500u processor, 8GB memory capacity, Ubuntu GNU/Linux 20.04 64-bit operating system. AMPL's solve command causes it to instantiate the current problem, send it to a solver, and attempt to read a solution computed by the solver [21].

3.2. Outputs of the Model

The GLPK solver produces a global integer optimal solution for the computer model developed in the GMPL (GNU MathProg), an open-source/free version implementation of the AMPL algebraic modeling language. The outputs of the computer model in the GMPL were compiled.

Vessels were dispatched to the shipyard for maintenance and repair in the most appropriate 2-week period during the year, with the other weeks either allocated by the business for its operations or chartered in a way to maximize profits. The penalty term was utilized in the modeling. The penalty term is based on hypothetical values given to the algorithm of the objective function so that it can attain the global optimal solution in a reasonable amount of time and in a practical manner. Removing this term from the objective function provides the present condition of the business. The yearly profit of the business is estimated to reach a maximum of 13,749,450 USD once all the assignments have been completed and modeled.

Based on the analysis of the data from the model solution in Table 3, in which weeks the vessels will be allocated by the business for its operations (x), in which weeks they can be chartered (y), or in which weeks they can be dispatched to the shipyard for maintenance and repair (z) are indicated. Although several weeks in Table 3 have similarities in terms of the present condition and modeling output, there are disparities in the assignment in general. While the corporation presently deploys primarily i2, i3, and i4 vessels for its own operations, a homogeneous distribution

Table 3. *Current state and post-modeling situation*

Weeks	Current situation in 2018						Post-modeling situation in 2018					
	i1	**i2**	**i3**	**i4**	**i5**	**i6**	**i1**	**i2**	**i3**	**i4**	**i5**	**i6**
1. Week		X	Y	X	Y		X	Y	X	Y	Y	Y
2. Week	X		Y		Y		X	Y	Y	Y	Y	Y
3. Week	Y	X	Y	X	Y	X	X	Y	Y	X	X	Y
4. Week	Y	X	Y	X	Y	X	X	X	Y	Z	Y	Y
5. Week	Y	X		X	Y		X	Y	Y	Z	Y	X
6. Week	Y	X		X	Y		Y	Y	X	X	Y	Y
7. Week	Y	X		X	Y		Y	Y	X	X	Y	Y
8. Week	Y	X		X	Y		Y	Y	X	Y	X	Y
9. Week	Y	X		X			Y	Y	X	Y	X	Y
10. Week	Y	X		X			Y	Y	X	Y	X	Y
11. Week		X	X	X			Y	Y	X	Y	X	X
12. Week			X	X	X	Y	Y	Y	X	Y	X	X
13. Week	X	X	X			Y	Y	Y	X	X	X	Z
14. Week	X	X	X	X		Y	X	X	X	Y	Y	Z
15. Week	X	X	X			Y	X	X	Z	Y	Y	X
16. Week		X		X		Y	Y	X	Z	Y	Y	X
17. Week		X	X	X		Y	Y	X	X	Y	Y	X
18. Week	X		X	X			Y	X	X	Y	X	Y
19. Week			X	X			Y	X	Y	Y	X	Y
20. Week				X			Y	Z	Y	Y	X	Y
21. Week			X				Y	Z	Y	Y	X	Y
22. Week		X	X	X	X		X	X	Y	Y	Y	Y
23. Week	X	X	X				X	X	Y	Y	Y	X
24. Week	X	X	X	X			X	X	Y	X	Y	X
25. Week	X	Y		X			X	Y	Y	X	Y	Y
26. Week	Y	Y	X	Y			Y	Y	Y	Y	X	Y
27. Week	Y	Y		Y			Y	Y	Y	Y	Y	Y
28. Week	Y	Y	X	Y			Y	Y	X	Y	Y	Y
29. Week	Y	Y	X	Y			Y	Y	Y	Y	Y	X
30. Week	Y	Y	Y	Y			Y	Y	Y	Y	Y	Y
31. Week	Y	Y	Y	X			Y	Y	Y	X	Y	Y
32. Week	Y	Y	Y				Y	Y	Y	Y	Y	Y
33. Week	Y	Y	Y	X			Y	Y	Y	Y	X	Y
34. Week	Y	Y	Y				Y	Y	Y	Y	Y	Y
35. Week	Y	Y		X			Y	Y	Y	Y	Y	X
36. Week	Y	Y	X				Y	Y	Y	Y	Y	X
37. Week	Y	Y					Y	Y	Y	Y	Y	Y
38. Week	Y	Y	X	X			Y	Y	X	Y	X	Y
39. Week	Y	Y	X	X			X	Y	Y	Y	Y	Y
40. Week			X	X			X	Y	Y	Y	Y	Y
41. Week	X					X	X	Y	Y	Y	Y	Y
42. Week			X	X		X	X	Y	Y	X	Y	X

Table 3. *Current state and post-modeling situation (Cont')*

Weeks	Current situation in 2018						Post-modeling situation in 2018					
	i1	i2	i3	i4	i5	i6	i1	i2	i3	i4	i5	i6
43. Week		X	X	X		X	Z	Y	X	X	Y	X
44. Week		X	X			X	Z	Y	X	X	Y	X
45. Week		X		X	X	X	X	Y	X	X	Y	X
46. Week		X	X	X	X	X	X	Y	X	X	X	X
47. Week	X	X	X	X	X	X	X	X	X	X	X	X
48. Week	X	X	X	X		X	X	X	X	X	Z	X
49. Week	X	X	X			X	X	X	X	X	Z	Y
50. Week	X	X	X	X		X	X	X	X	X	X	Y
51. Week	X	X	X	X		X	X	X	X	X	X	Y
52. Week	X	X	X	X		X	X	X	X	X	X	Y

of ship assignments has appeared in general, despite the fact that i1 and i3 vessels are the most often utilized in the model output. All available vessels were currently allocated by the business for its operations during the period from mid-October until the end of the year, when the voyage density surged, although this condition slightly differed in the model output. The i6 vessel was chartered in particular during the last four weeks of the year, whereas the i5 vessel was chartered during the 48th and 49th weeks. The present condition and model output of the i2 vessel, one of the vessels most frequently deployed by the business for its own operations, was produced in a fundamentally different way. Currently, the business operations were assigned 28 weeks, compared to 16 weeks in the model output. In the model output, the i3 vessel, which the business presently deploys extensively in its own operations, was also evaluated differently. The i3 vessel was chartered for a total of 9 weeks during the year, whereas the model output was chartered for a total of 26 weeks. The business has now assigned the i3 vessel 29 weeks for its operations, but the model has only assigned 24 weeks, with 10 weeks accomplished in the last quarter of the year. In the model output, the i4 vessel was assigned to the charter for 32 weeks, making it one of the most assigned ships to the charter market. The model assigned the i4 vessel by the business for its operations for a total of 18 weeks and 11 uninterrupted weeks during the peak voyages.

To test the model and compare yearly net incomes, Table 4 provides the income-expenditure balance of the current operation, charter, and idle waiting circumstances through a calculation of the collected data. According to the data from 2018, the annual net profit was 9,415,087 USD, which was 13,749,450 USD once the penalty term was removed from the model output. Therefore, the business profit increased by 46%.

Table 4. *Annual net profit for the current situation in 2018*

	Revenue	Cost
Operation	14,773.941	5,334.984
Charter	2,111.930	952.000
Lay-up cost	---	1,185.800
Total	16,887.871	8,333.775
Net profit	**9.415.087 USD**	

3.3. Scenario-Based Solutions of the Model

The profit maximization model based on marine transportation and fleet planning optimization was tested, and its reliability was verified. In the next step, the model was run again with the changes in the parameters. "Cargo demands" and "vessel numbers" were among the parameters defined in the mathematical model that was changed again based on scenarios, and the model was run again. The scenarios considered for the cargo demand and fleet reduction were optimistic and pessimistic. The goal of producing different scenarios is to identify what kind of demand changes may happen and what kind of measures that the business might take.

The first scenario produced for the model was based on data supplied by the port authorities and was deemed an optimistic circumstance. The model was defined and solved based on the weekly vehicle transportation scenario in 2015 when transportation was at its peak between 2014 and 2018. Table 5 depicts the present position and the outcome of the optimistic scenario. A total profit of 16,784,977 USD was achieved as a consequence of the solution. Based on the review of the vessel assignments, the i1 and i4 vessels were the two most assigned by the business for its operations in the modeling output as a consequence of the optimistic scenario.

Table 5. *Optimistic and pessimistic scenarios based the solution results of the model*

Weeks	Current situation in 2018						Optimistic scenario result						Pessimistic scenario result					
	i1	i2	i3	i4	i5	i6	i1	i2	i3	i4	i5	i6	i1	i2	i3	i4	i5	i6
1. Week		X	Y	X	Y		Y	Y	Y	X	X	Y	Y	Y	Y	Y	Y	Y
2. Week	X		Y		Y		Y	Y	Y	X	X	Y	Y	Y	Y	Y	Y	Y
3. Week	Y	X	Y	X	Y	X	X	Y	Y	X	X	Y	Y	Y	Y	X	Y	Y
4. Week	Y	X	Y	X	Y	X	X	Y	Y	Y	X	X	Y	Y	Y	X	Y	Y
5. Week	Y	X		X	Y		X	Z	X	Y	X	X	Y	Y	Y	Y	Y	Y
6. Week	Y	X		X	Y		X	Z	X	Y	X	X	X	Y	X	Y	Y	Y
7. Week	Y	X		X	Y		X	X	X	Y	Z	Y	X	Y	X	Y	Y	Y
8. Week	Y	X		X	Y		X	X	Z	X	Z	Y	X	Y	X	Y	X	Y
9. Week	Y	X		X			X	X	Z	Y	X	Y	Y	X	Y	Y	X	Y
10. Week	Y	X		X			X	X	X	Y	Y	Y	Y	Z	Y	X	X	Y
11. Week		X	X	X			X	X	X	Y	Y	Y	Y	Z	Y	Y	X	Y
12. Week			X	X	X	Y	X	X	X	Y	Y	Y	Y	Y	Y	Y	X	Y
13. Week	X	X	X			Y	X	Y	X	Y	Y	Y	X	Y	Y	Y	X	Y
14. Week	X	X	X	X		Y	X	Y	X	Y	Y	Y	Y	Y	Y	Y	X	Y
15. Week	X	X	X			Y	Y	Y	X	X	X	Y	Y	Y	X	Y	Y	Y
16. Week		X		X		Y	Y	Y	X	Y	X	Y	Y	Y	X	Y	Y	Y
17. Week		X	X	X		Y	Y	Y	X	Y	X	X	Y	X	X	Y	Y	X
18. Week	X		X	X			Y	X	X	Y	X	Y	Y	Y	X	X	Y	Y
19. Week			X	X			X	X	Y	Y	X	Y	Y	Y	Y	Z	X	Y
20. Week				X			X	X	Y	X	Y	Y	X	Y	Y	Z	Z	Y
21. Week			X				X	X	Y	X	Y	Y	Z	Y	Y	X	Z	Y
22. Week		X	X	X	X		X	X	Y	X	Y	Y	Z	Y	Y	Y	X	X
23. Week	X	X	X				X	X	Y	X	Y	Y	X	Y	Y	Y	X	Y
24. Week	X	X	X	X			X	X	Y	X	Y	Y	Y	Y	Y	Y	X	Y
25. Week	X	Y		X			X	X	Y	X	Y	Y	Y	Y	Y	Y	X	Y
26. Week	Y	Y	X	Y			X	X	Y	X	Y	Y	Y	Y	Y	Y	X	Y
27. Week	Y	Y		Y			X	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
28. Week	Y	Y	X	Y			Y	Y	Y	Y	X	Y	Y	Y	Y	Y	Y	Y
29. Week	Y	Y	X	Y			Y	Y	Y	Y	X	Y	Y	Y	Y	Y	Y	Y
30. Week	Y	Y	Y	Y			Y	Y	Y	Y	X	Y	Y	Y	Y	Y	Y	Y
31. Week	Y	Y	Y	X			Y	Y	Y	Y	X	Y	Y	Y	Y	Y	Y	Y
32. Week	Y	Y	Y				Y	Y	Y	X	Y	X	Y	Y	Y	Y	Y	Y
33. Week	Y	Y	Y	X			Y	Y	Y	X	Y	X	Y	Y	Y	Y	Y	Y
34. Week	Y	Y	Y				Y	Y	Y	X	Y	X	Y	Y	Y	Y	Y	Y
35. Week	Y	Y		X			Y	Y	Y	X	Y	X	Y	Y	Y	Y	Y	Y
36. Week	Y	Y	X				Z	Y	Y	X	Y	X	Y	Y	Y	Y	Y	Y
37. Week	Y	Y					Z	Y	Y	Z	X	X	Y	Y	Y	Y	Y	Y
38. Week	Y	Y	X	X			Y	Y	X	Z	X	Z	X	Y	Y	Y	Y	Y
39. Week	Y	Y	X	X			Y	Y	X	X	Y	Z	Y	Y	Y	Y	X	X
40. Week			X	X			Y	Y	Y	X	Y	X	Y	X	Y	Y	Y	Z
41. Week	X					X	Y	Y	Y	X	Y	X	Y	X	Y	Y	Y	Z
42. Week			X	X		X	X	X	Y	X	Y	X	Y	Y	Z	X	Y	X

Table 5. *Optimistic and pessimistic scenarios based the solution results of the model (Cont')*

Weeks	Current situation in 2018						Optimistic scenario result						Pessimistic scenario result					
	i1	i2	i3	i4	i5	i6	i1	i2	i3	i4	i5	i6	i1	i2	i3	i4	i5	i6
43. Week		X	X	X		X	X	X	Y	X	Y	X	X	Y	Z	X	Y	X
44. Week		X	X			X	X	X	Y	X	Y	X	X	Y	X	X	X	X
45. Week		X		X	X	X	X	X	Y	X	Y	X	X	Y	X	X	X	X
46. Week		X	X	X	X	X	X	X	X	X	X	X	X	Y	X	X	X	X
47. Week	X	X	X	X	X	X	X	X	X	X	X	X	X	Y	X	X	Y	X
48. Week	X	X	X	X		X	X	X	X	X	X	X	X	Y	X	X	Y	X
49. Week	X	X	X			X	X	X	X	X	X	X	X	X	X	X	Y	X
50. Week	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	Y	X
51. Week	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	Y	X
52. Week	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	Y	X

The i2 and i3 vessels were assigned by the business for its operations for a total of 26 and 21 weeks, respectively, whereas the i5 and i6 vessels were assigned by the business for its operations for a total of 23 and 21 weeks, respectively. During the last seven weeks of the year, when transportation was particularly heavy, all vessels were assigned by the business for its operations. When the present condition in 2018 and the total profits of the optimistic scenario were compared, a profit rise of 78.27% emerged.

The second scenario produced in the study was defined as the pessimistic scenario in the model. The pessimistic scenario is also based on the data in 2016 when the business transported the fewest vehicles from 2014 to 2018. The aircraft crash in 2016 interrupted Türkiye-Russia ties, and the political crisis had a significant impact on trade between the two states. Table 5 shows the vessel assignments that appeared after the pessimistic scenario was run. After the pessimistic scenario modeling, the total profit was 11,451,743 USD. In the table that was created as a result of the pessimistic scenario, the model i2 vessel was assigned for only 8 weeks for its own operations and chartered the remaining weeks. The i1 vessel, the second-largest vessel of the fleet, and the i5 vessel, one of the smallest vessels of the fleet, were both assigned by the business for its operations for a total of 17 weeks. The model assigned the i3 and i4 vessels of the fleet with the same capacity to the businesses own operations for 16 weeks. The i6 vessel, one of the smallest vessels in the fleet, was assigned to the company's own operations for a total of 14 weeks and saved for the two weeks when the vessel was dispatched to the shipyard. It was deemed appropriate to be chartered by the model for the remaining weeks. Generally, all vessels, with the exception of the i2 vessel, were assigned homogeneously for the business' own operations throughout the year. When the present condition in 2018 and the total profits of the pessimistic scenario were compared, a profit rise of 21.63% was noticed. Despite the pessimistic scenario, the model demonstrated that the present condition might provide a greater profit.

Table 6 shows the output findings for the present condition, pessimistic scenario, and optimistic scenario. For the comparison of the three scenarios, this problem was solved with a laptop with a GLPK integer optimizer v4.65 linear and integer program solver, AMD® Ryzen 5 3500u processor, 8GB memory capacity, and Ubuntu GNU/Linux 20.04 64-bit operating system. The optimistic scenario of 2015, in which the business transported the most vehicles from 2014 to 2018; the pessimistic scenario of 2016, in which the business transported the least vehicles from 2014 to 2018; and the present condition in 2018 were based when determining the scenarios. The GLPK solver was unable to solve the problem without utilizing mixed-integer rounding (MIR) truncation algorithms, and it was not possible to solve the scenarios because the solver was trapped in the memory/time limit. Therefore, enabling the MIR option of the GLPK solver to solve this problem instance makes a significant difference in the computing performance. The resulting objective functions did not develop as expected because the scenarios were based on scenarios, and the optimistic scenario outperformed the present condition, whereas the pessimistic scenario underperformed it.

Another scenario produced was to reduce the number of vessels. Within the framework of the scenario, the i5 and i6 vessels with a capacity of 54 trailers, the least deployed in the business operations, were withdrawn from the fleet in order. Table 7 presents a comparison between the present condition and the outputs of the scenario. The comparison we undertook with MIR made it easier for us to arrive at

Table 6. *Load-based scenario comparison*

		Pessimistic scenario	Current situation	Optimistic scenario
With MIR interruptions	Problem	Pessimistic	Current	Optimistic
	Line	1,553	1,553	1,553
	Column	988 (936 integer, 936 binary)	988 (936 integer, 936 binary)	988 (936 integer, 936 binary)
	Coefficient different from 0	7,016	7,016	7,016
	Problem status at end of run	Integer Optimal	Integer Optimal	Integer Optimal
	Objective function	-187548257 (Max) (11451743 After removing the Slack variable, the max. profit)	-377250550 (Max) (13749450 After removing the Slack variable, the max. profit)	-160215023 (Max) (16784977 After removing the Slack variable, the max. profit)
	Time used	213.3 sec.	17063.2 sec.	67.0 sec.
	Memory used	23.0 Mb	499.1 Mb	11.0 Mb

MIR: Mixed-integer rounding

Table 7. *Vessel-based scenario comparison*

		Current situation	i5 vessel is sold	i6 vessel is sold
With MIR interruptions	Problem	Current situation	I5 vessel is sold	I6 vessel is sold
	Line	1,553	1,303	1,303
	Column	988 (936 integer, 936 binary)	832 (780 integer, 780 binary)	832 (780 integer, 780 binary)
	Coefficient different from 0	7,016	5,864	5,864
	Problem status at the end of the run	Integer optimal	Integer optimal	Integer optimal
	Objective function	-377250550 (Max) (13749450 Slack After removing the Slack variable, the max. profit)	-530868119 (Max) (13131881 After removing the Slack variable, the max. profit)	-530832567 (Max) (13167433 After removing the Slack variable, the max. profit)
	Time used	17063.2 sec.	864.1 sec.	957.2 sec.
	Memory used	499.1 Mb	66.1 Mb	83.3 Mb

MIR: Mixed-integer rounding

our conclusion. The model output compared two i5 and i6 vessels, which were operated at least in the business' operations, by removing out of the fleet in order. The aim is to find an answer to the question of which vessels will be least affected by downsizing if the company decides to do so. Although everything is the same, i.e., sister (sister) vessels, the differences in the daily charter prices and monthly average incomes have caused us to attain different objective functions.

The model was run again for the remaining five vessels after being withdrawn from the fleet, and the results are presented in Table 8. As a consequence, in contrast to Table 3, some changes took place in the weekly assignments of the i5 and i6 vessels. In the comparison between the i5 and i6 vessels, a change was noticed only in the weeks when they were dispatched to the shipyard. Furthermore, the weeks when the i4 vessel was dispatched to the shipyard have changed, and the i5 vessel was dispatched to the shipyard between the 22nd and 23rd weeks in the scenario when it was withdrawn from the fleet. Meanwhile, the i6 vessel was dispatched to the shipyard in the 4th and 5th weeks when it was removed from the fleet.

Disparities were observed between the present condition modeling and the scenarios in the weekly assignments of the vessels as a consequence of the last scenarios produced. The weeks in which only vessels have to be dispatched to the shipyard are the same in all three cases for the i1, i2, and i3 vessels. Moreover, there is a disparity in the profit to be generated as a result of the i5 and i6 vessels being withdrawn from the fleet in order. If the i5 vessel was withdrawn from the fleet, the maximum profit was calculated to be 13,131,881 USD, and if the i6 vessel was withdrawn from the fleet, the maximum profit was determined to be 13,167,433 USD. The difference was approximately 34,000 USD. When the

Table 8. *Result of the model's ship reduction scenario-based solution*

Weeks	**Post-modeling situation in 2018**						**Disclaimer of the i5 vessel from the fleet**					**Disclaimer of the i6 vessel from the fleet**				
	i1	**i2**	**i3**	**i4**	**i5**	**i6**	**i1**	**i2**	**i3**	**i4**	**i6**	**i1**	**i2**	**i3**	**i4**	**i5**
1. Week	X	Y	X	Y	Y	Y	X	Y	X	Y	Y	X	Y	X	Y	Y
2. Week	X	Y	Y	Y	Y	Y	X	Y	Y	Y	Y	X	Y	Y	Y	Y
3. Week	X	Y	Y	X	X	Y	X	X	Y	X	Y	X	X	Y	X	Y
4. Week	X	X	Y	Z	Y	Y	X	X	Y	Y	Y	X	X	Y	Z	Y
5. Week	X	Y	Y	Z	Y	X	X	Y	Y	Y	X	X	Y	Y	Z	X
6. Week	Y	Y	X	X	Y	Y	X	Y	Y	Y	X	X	Y	Y	Y	X
7. Week	Y	Y	X	X	Y	Y	X	Y	Y	Y	X	X	Y	Y	Y	X
8. Week	Y	Y	X	Y	X	Y	Y	Y	X	Y	X	Y	Y	X	Y	X
9. Week	Y	Y	X	Y	X	Y	Y	Y	X	Y	X	Y	Y	X	Y	X
10. Week	Y	Y	X	Y	X	Y	Y	Y	X	Y	X	Y	Y	X	Y	X
11. Week	Y	Y	X	Y	X	X	Y	Y	X	X	X	Y	Y	X	X	X
12. Week	Y	Y	X	Y	X	X	Y	Y	X	X	X	Y	Y	X	X	X
13. Week	Y	Y	X	X	X	Z	Y	Y	X	X	X	Y	Y	X	X	X
14. Week	X	X	X	Y	Y	Z	X	Y	X	X	X	X	Y	X	X	X
15. Week	X	X	Z	Y	Y	X	Y	X	Z	X	X	Y	X	Z	X	X
16. Week	Y	X	Z	Y	Y	X	Y	X	Z	Y	X	Y	X	Z	Y	X
17. Week	Y	X	X	Y	Y	X	Y	X	X	Y	X	Y	X	X	Y	X
18. Week	Y	X	X	Y	X	Y	Y	X	X	Y	X	Y	X	X	Y	X
19. Week	Y	X	Y	Y	X	Y	Y	X	Y	Y	X	Y	X	Y	Y	X
20. Week	Y	Z	Y	Y	X	Y	Y	Z	Y	Y	X	Y	Z	Y	Y	X
21. Week	Y	Z	Y	Y	X	Y	Y	Z	Y	Y	Z	Y	Z	Y	Y	X
22. Week	X	X	Y	Y	Y	Y	X	X	Y	Z	Z	X	X	Y	Y	Z
23. Week	X	X	Y	Y	Y	X	X	X	Y	Z	X	X	X	Y	X	Z
24. Week	X	X	Y	X	Y	X	X	X	Y	X	X	X	X	Y	X	X
25. Week	X	Y	Y	X	Y	Y	X	Y	Y	X	Y	X	Y	Y	X	Y
26. Week	Y	Y	Y	Y	X	Y	Y	Y	Y	X	Y	Y	Y	Y	X	Y
27. Week	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
28. Week	Y	Y	X	Y	Y	Y	Y	Y	X	Y	Y	Y	Y	X	Y	Y
29. Week	Y	Y	Y	Y	Y	X	Y	Y	Y	Y	X	Y	Y	Y	Y	X
30. Week	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
31. Week	Y	Y	Y	X	Y	Y	Y	Y	Y	X	Y	Y	Y	Y	X	Y
32. Week	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
33. Week	Y	Y	Y	Y	X	Y	Y	Y	X	Y	Y	Y	Y	X	Y	Y
34. Week	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
35. Week	Y	Y	Y	Y	Y	X	Y	Y	Y	Y	X	Y	Y	Y	Y	X
36. Week	Y	Y	Y	Y	Y	X	Y	Y	Y	Y	X	Y	Y	Y	Y	X
37. Week	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
38. Week	Y	Y	X	Y	X	Y	X	Y	X	Y	Y	X	Y	X	Y	Y
39. Week	X	Y	Y	Y	Y	Y	X	Y	Y	Y	Y	X	Y	Y	Y	Y
40. Week	X	Y	Y	Y	Y	Y	X	Y	Y	Y	Y	X	Y	Y	Y	Y
41. Week	X	Y	Y	Y	Y	Y	X	Y	Y	Y	Y	X	Y	Y	Y	Y

Table 8. *Result of the model's ship reduction scenario-based solution (Cont')*

Weeks	Post-modeling situation in 2018						Disclaimer of the i5 vessel from the fleet					Disclaimer of the i6 vessel from the fleet				
42. Week	X	Y	Y	X	Y	X	X	Y	Y	X	X	X	Y	Y	X	X
43. Week	Z	Y	X	X	Y	X	Z	Y	X	X	X	Z	Y	X	X	X
44. Week	Z	Y	X	X	Y	X	Z	Y	X	X	X	Z	Y	X	X	X
45. Week	X	Y	X	X	Y	X	X	Y	X	X	X	X	Y	X	X	X
46. Week	X	Y	X	X	X	X	X	X	X	X	X	X	X	X	X	X
47. Week	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
48. Week	X	X	X	X	Z	X	X	X	X	X	X	X	X	X	X	X
49. Week	X	X	X	X	Z	Y	X	X	X	X	X	X	X	X	X	X
50. Week	X	X	X	X	X	Y	X	X	X	X	X	X	X	X	X	X
51. Week	X	X	X	X	X	Y	X	X	X	X	X	X	X	X	X	X
52. Week	X	X	X	X	X	Y	X	X	X	X	X	X	X	X	X	X

scenarios were compared to the model's baseline output, an average profit reduction of 4.3% was observed.

4. Conclusion

Fleet planning is vitally important for Ro-Ro transportation businesses. It does not merely support the operation, but it also aids businesses in determining the levels at which they should get into the charter market. Fleet planning has many aspects other than operational costs and revenues, considering that non-operational activities, such as maintenance and repairing expenditures that are directly part of the overall costs, should be considered a part of the fleet planning process.

In this study, a ship management firm which operates a Ro-Ro transportation business in the Black Sea Region was examined, and a profit maximization natured idle capacity penalizing multi-objective function was identified as the objective function of the fleet planning problem instance. Considering the revenues generated and expenditures incurred from "in-house" and chartering operations, most of the parameters of the mathematical model that would give the fleet plan were derived from respective sources. Six Ro-Ro vessels that operate on the Samsun-Russia line of this maritime business were included in the scope of the research. Finally, the optimal fleet plan consisting of vessel assignment outcomes were accomplished. When the model was run on real-world data, the optimum plan utilizing the vessels was at an optimum level, thus ensuring that profit maximization under the model's constraints has been achieved. Accordingly, the findings support the expected outcomes concerning assignment timings of the fleet. In other words, except the times of the year when the domestic transportation load is high, the model assures resorting to chartering vessels in the fleet and never allows vessels to stay idle within the planning horizon, thus generating more income for the business. The applicability of the model has also been put forward by evaluating optimistic, pessimistic, and vessel landing scenarios along with the current setting.

Although the model was specifically developed for the fleet of a vessel operating business that engages in Ro-Ro transportation in the Black Sea Region, the model can be practically extended and scaled up for many instances in the maritime sector, such as businesses with different fleet sizes and characteristics, especially in the field of regular line transportation. The geographical and business distinctions would not affect the validity or applicability of the model, even if it might be more suitable for various settings having a diversified portfolio that would encourage enhancing the adaptability. The model may be improved by adding additional parameters and constraints based on a variety of real-life scenarios and data available from vessel operating businesses.

On another note, during the research conducted for this study, we have observed that even basic mathematical planning notion is still missing within the industry. The reason behind this unawareness for utilizing mathematical planning for getting better operational outcomes might have roots in many different places, which have been held out of the scope of this paper and might be considered a local problem. However, we believe that there is a lot of room for improving the operating performances of Turkish maritime businesses by employing mathematical planning techniques at any level within many problem domains starting with fleet planning.

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Examining the Cointegration Relationship Between the Container Trade in the Mediterranean and the Level of Labor Force Participation: A Panel Data Study

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Abstract

Today, container transportation and intermodal connections by sea contribute significantly to the economic activities and trade volume of the nation and region where the transportation is conducted. This study evaluates the volume of containers handled between 2000 and 2020 in the ports of Türkiye, Greece, Italy, and Spain in the Mediterranean Basin, as well as the labor force, and determines whether the two variables are co-integrated. The Organization for Economic Co-operation and Development provided information on the volume of containers handled in TEUs, and the World Bank provided information on the labor force. Two variables were tested for cross-sectional dependency, homogeneity, second-generation panel unit root, panel cointegration, and causality. Although a long-term relationship between the two variables could not be determined as a result of the analysis, it was determined that the two variables were Granger causes of each other and had a bidirectional causality relationship. In this context, it is evident that both data substantially impact one another. The results indicate that the maritime sector responds to changes in a country's economy and trade volume through a short-term decrease or increase in capacity.

Keywords: Maritime transportation, Container trade, Labor force participation, Cointegration

1. Introduction

Maritime transport is a mode of transport that, when combined with other modes of transport, allows for large amounts of cargo to be transported over long distances at a low cost. Because waterways carry a large portion of global trade, maritime transport is the backbone of the global economy and trade. Furthermore, it plays a significant role in global logistics activities and is directly affected by economic growth and global trade developments.

Container transportation, which plays an important role in maritime, has grown in popularity as global trade has improved. Container transportation and related logistics services, in addition to being a part of the supply chain, contribute to the socioeconomic development of countries and serve as an indicator in the evaluation of economic size. By regional and international container routes, the Mediterranean is an important region, and ports compete for a larger share of container shipping. The purpose of this research is to determine whether there is cointegration between the volume of containers handled in the ports of Türkiye, Greece, Italy, and Spain, which compete with each other in the Mediterranean container trade, and the level of the labor force in these countries, and to make a result-oriented situation assessment.

When the economic effects of container transportation are considered, it is believed that there is a directly proportional relationship between the change in the volume of containers handled in a country's ports and its labor force. Although there have been many studies on the relationship between container transportation and trade volume, economic activities, and country sizes, there has only been one study on the relationship between the change in the volume of

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containers handled at ports and the labor force. Bottasso et al. [1] discovered a positive relationship between regional employment and port volume using panel data analysis in their study. Furthermore, we have not encountered a study in which Türkiye was also evaluated in the literature. Therefore, panel data analysis is used in this context to assess the impact of the volume of containers handled in the ports of Türkiye, Greece, Italy, and Spain on the labor force in these countries.

Container transportation is one of the factors reshaping the port and maritime industries [2,3]. The integration of logistics modes and positive trade developments increase the volume of container transportation, which provides global intermodal transportation. As a result, the supply chain's functionality of ports, which are key points of global container transportation, improves. The increased use of containers in international trade has allowed ports to improve their infrastructure and superstructure for container handling [4,5]. As a result, container terminal volume and capacity have increased, particularly in ports with integrated systems, and storage and distribution services have improved. Container transportation and port operations are now regarded as important indicators in assessing international trade and a country's economic size, as well as being a component of the transportation system [6,7].

The Mediterranean Sea and its countries play an important role in maritime trade. The Mediterranean Sea is a maritime area served by regional and international routes in world container transportation. Furthermore, the region's container transportation volume is constantly increasing, contributing to socioeconomic development [8]. In particular, ports in the Eastern and Central Mediterranean compete for a larger share of container transportation. In this context, Türkiye emphasizes its practices to lower logistics costs, shorten transit transportation times, increase the rate of undamaged delivery, and increase speed and reliability [9]. Based on the competition in the region, a study will be conducted to reveal and emphasize the importance of the Mediterranean in global container transportation. The goal of this study is to see if there is a cointegration between the two variables based on the volume of containers handled in the ports of Türkiye, Greece, Italy, and Spain, which compete in the Mediterranean container trade, and the labor force in these countries between 2000 and 2020. The study begins by assessing the effects of container transportation on trade and the economy. Second, the relationship between the volume of containers handled and the labor force in the countries studied is examined. Finally, a situation assessment for the subject of the study is performed, and recommendations are presented.

2. Literature Review

The development of container transportation has resulted in a shift in maritime freight transportation. General and special cargoes are thus delivered more quickly, safely, and securely to their destinations [10]. Furthermore, intermodal freight movements between ships, trains, and trucks increase carrying capacity [4].

Container transportation comprises three basic components: cargo, carrier, and port. Adding a new container terminal to the schedule of a container carrier is a factor that accelerates commercial development in the destination area [11]. Port service capacity grows with cargo and ship traffic [12]. Increased performance in container ports improves production efficiency, including labor and capital [13]. On the other hand, the decrease in cargo volume during crisis periods reduces port transaction volumes and, thus, the countries' growth rates [14].

Several studies have been conducted on the relationship between container transportation and countries' trade volume, size, and economic activity. According to Luo and Grigalunas [15], the importance of a well-planned container port on intermodal transportation costs and its economic impact on the markets served is significant. According to Hall [16], large ports serve producers and consumers in a broad hinterland, which impacts the employment structure in ports and port-related sectors. Using panel data analysis, Bottasso et al. [1] discovered a positive relationship between regional employment and port transaction volume in their study. Takım and Ersungur [17] emphasized the significance of container volume handled at ports in Türkiye's foreign trade. Ünver [18] used unbalanced panel data analysis to reveal the effect of maritime transport connectivity on the export level of economies. In their study on the foreign trade volume by transportation type in Türkiye, Emirkadı and Balcı [19] mentioned the importance of container transportation. According to Hlali and Hammami's [20] research, container port development provides economic development for all modes of transportation. According to Özer et al. [21], maritime container transportation has a positive and statistically significant effect on short- and long-term economic growth. Using the panel vector autoregressive approach, Michael et al. [6] demonstrated that container trade is an important determinant of GDP growth. Dördüncü's [22] study used the Toda-Yamamoto causality analysis to test the interaction between the amount of export and container transportation and discovered that changes in exports affected the volume of containers handled and the number of TEUs. Using a panel data regression model, Fartila-Adam et al. [23] discovered that maritime transport, air pollutants caused by maritime transport, and investment in port infrastructure are positively related to economic growth. Tunalı and Akarçay [24] used panel cointegration analysis to examine the relationship between the GDP growth of container transportation and port infrastructure investments and concluded that container transportation and port infrastructure investments had a positive effect on economic growth (Table 1).

When the economic effects of container transportation are considered, it is believed that there is a positive relationship between the change in the volume of containers handled at a country's ports and its labor force. However, only one study on the relationship between the change in the volume of containers handled at ports and the labor force was found in the literature review. However, we have not found a study in which Türkiye was evaluated. In this regard, panel data analysis is used to assess the impact of the volume of containers handled in the ports of Türkiye, Greece, Italy, and Spain on the workforce in these countries.

3. Methodology

Panel data analysis was used in this study to determine whether there is a cointegration between the volume of containers handled in the Mediterranean Basin container trade in Türkiye, Greece, Italy, and Spain between 2000 and 2020.

The study of cross-sectional units over time is referred to as panel data analysis [25]. A cross-sectional data set in this framework consists of observations on a specific number of variables at a specific time [26]. Panel data is used to gather information about multiple units in a time series [27]. Panel datasets are comprised of individuals and time series; in this context, issues like stationarity vs. non-stationarity and causality vs. non-causality of time series econometrics arise [28]. The superior aspects of the analysis enable the control and measurement of distinct properties of the same units. More comprehensive studies can be conducted because it combines cross-sectional and time series data [25,29,30].

To achieve the study's goal, data on the volume of containers handled in TEUs between 2000 and 2020 were obtained from the Organization for Economic Co-operation and Development (OECD) [31], and data on the associated labor force were obtained from World Bank (WB) [32] websites. For the study, the following hypotheses were developed.

H1: There is a cointegration relationship between the volume of containers transported by sea and the total labor force employed.

H2: The volume of containers transported by sea and the total labor force are the Granger causes of each other.

The Stata and EViews software packages were used to test the hypotheses. EViews is a statistical package program for Windows that is primarily used for econometric testing and analysis. It statistically analyzes the relationships between variables and allows for analyses with cross-sectional data, time series data, and panel data to make predictions and future predictions [33]. The Stata program facilitates and accelerates statistical analysis when working with large and complex quantitative data sets with varying file structures. It is used to cluster statistically significant data obtained after panel data analysis [34]. Similarly, Stata is a software package that includes statistical and econometric testing and analysis, as well as data science, visualization, and extensible reporting. While EViews and Stata are capable of general statistical analysis, their primary applications

Table 1. *Some research on the relationship between container transportation and trade volume, economic activities, and sizes of countries*

Author	Year	Data	Method
Bottasso et al. [1]	2013	Statistical Data	GMM-System Estimator
Yıldırım et al. [48]	2013	Statistical Data	Standard and Multiple Break Unit Root
Alper and Oransay [39]	2015	Statistical Data	Panel Causality Analysis
Ünver [18]	2016	Statistical Data	Unbalanced Panel Data Analysis
Kar et al. [44]	2018	Statistical Data	Panel Cointegration Analysis
Turgut and Uçan [43]	2019	Statistical Data	Panel Data Analysis
Çelik and Ünsür [30]	2020	Statistical Data	Panel Causality Analysis
Demir and Görür [27]	2020	Statistical Data	Panel Cointegration Analysis
Okşak and Sarıtaş [25]	2020	Statistical Data	Panel Data Analysis
Özer et al. [21]	2021	Statistical Data	Autoregressive Distributed Lag
Dördüncü [22]	2021	Statistical Data	Toda-Yamamoto Causality Analysis
Fartila-Adam et al. [23]	2021	Statistical Data	Panel Data Regression Analysis
Michael et al. [6]	2021	Statistical Data	Panel Vector Autoregressive
Tunalı and Akarçay [24]	2022	Statistical Data	Panel Cointegration Analysis

are regression and econometric analysis. EViews and Stata, both of which support Excel and SPSS program types, can test panel data, time series, and cross-sectional analysis. The hypotheses were tested using the Westerlund panel cointegration test [35] and the Dumitrescu and Hurlin [36] causality test. The Granger test is one of the most commonly used causality tests in the literature. According to Clive Granger's analysis in his 1969 study titled "Investigating Causal Relations by Econometric Models and Cross-Spectral Methods," if the variable y is predicted better when the variable x is used than when it is not used, the variable x causes y [37]. The Westerlund test was used because it accounts for structural breaks and cross-sectional dependence. Because it is an adapted version of the Granger-causality test for heterogeneous panel data analysis, the Dumitrescu and Hurlin [36] test was chosen [38]. This method considers the panel's cross-sectional dependence and heterogeneity; it can also be used when the time dimension is larger or smaller than the cross-sectional dimension, producing effective results in unbalanced panel data sets [39].

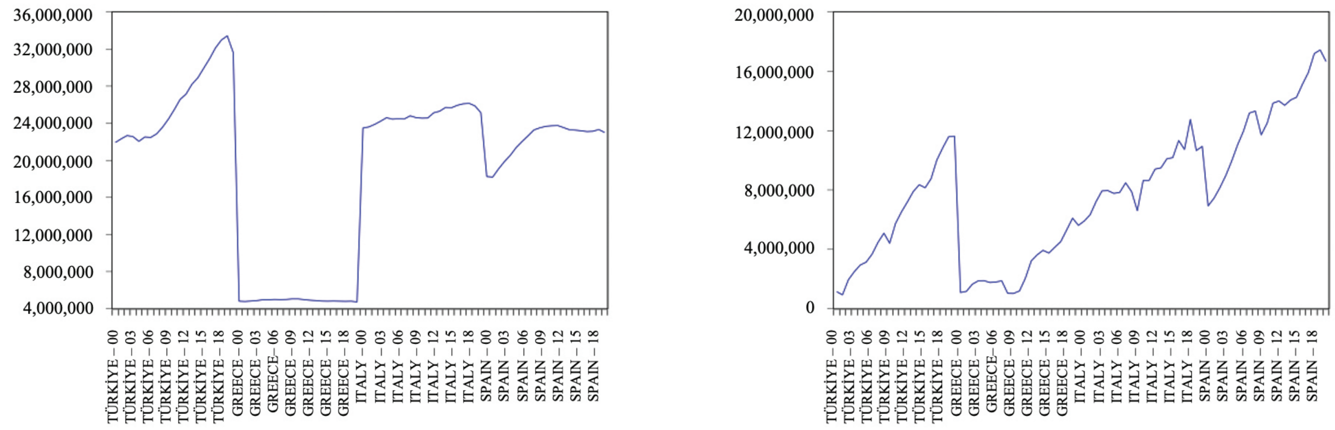
Figure 1 depicts the level graphs of the series concerning the total labor force by country and the volume of containers handled in TEUs of the countries in the analysis.

4. Findings and Discussion

4.1. Cross-Sectional Dependency Test Results

In cross-sectional dependency analysis, various tests can be used. Before testing the cointegration relationship between the series in econometrics, the Breusch and Pagan [40] LM (lagrange multiplier) test, Pesaran [41] CD and CD-LM (cross sectional dependent-lagrange multiplier) tests and Pesaran et al. [42] deviating corrected horizontal cross-sectional tests are used to determine whether there is an dependence between the horizontal sections that comprise the panel. Breusch and Pagan [40] uses the LM test when the time dimension is greater than the cross-sectional dimension (T>N), and Pesaran [41] uses the CD test when both the time dimension and the cross-sectional dimension are greater than the time dimension (T>N, N>T). Unfortunately, these tests are biased when the group mean is zero, but the individual mean is not zero. Pesaran et al. [42] corrected this error by incorporating the variance and mean into the test statistic. As a result, it is known as the deviation-corrected LM test.

The Breusch and Pagan [40] test is used in this framework because the panel's time dimension is greater than its cross-sectional dimension [43]. Table 2 displays the



Regarding Total Number of Labor Force by Countries Series Level Chart

Level Graph of the Series Regarding the Amount of Containers Handled in TEUs by Country

Figure 1. *Time graph of variables*

Table 2. *Container volume-horizontal sectional dependency test results*

Test	Statistic	d.f.	Prob.
Breusch-Pagan LM	102.7159	6	0.0000
Pesaran scaled LM	27.91948		0.0000
Bias-corrected scaled LM	27.81948		0.0000
Pesaran CD	10.12359		0.0000

cross-sectional dependency test results for the volume of containers handled at the ports of Türkiye, Greece, Italy, and Spain, which are the subject of the study. As a result, the null hypothesis in the Breusch and Pagan [40] LM cross-sectional dependency test is "there is no cross-sectional dependency," and the null hypothesis is rejected at the 5% significance level when the probability value for all test statistics obtained for the volume of containers handled variable in TEUs of countries is examined. As a result, there is a cross-sectional dependency in the variable related to the volume of containers handled in the panel's units. In this framework, panel unit root test and panel cointegration tests, which are used in cases of cross-sectional dependence, were used for further study.

Another variable in Table 3, the null hypothesis of "there is no cross-sectional dependence" for the labor force in the total population, is also rejected at the 5% significance level. There is a cross-sectional dependency in this variable, as in the variable related to the volume of containers handled. Therefore, due to the cross-sectional dependency, second-generation panel unit root and panel cointegration tests were applied to the variable of "the labor force in the total population" in subsequent sections of the study.

4.2. Homogeneity Test Results

The homogeneity test determines whether any of the selected countries are affected at the same level by changes in the "volume of containers handled" and the other variable, "the labor force," as Türkiye, Greece, Italy, and Spain. The economic situation of the countries is critical in this case. If the economic conditions of the countries differ, the coefficients within the framework of the model are expected to be heterogeneous. The coefficients should be homogeneous if the countries' economic conditions are similar [43,44]. For the homogeneity test, the Hsiao multivariate Granger-causality test was used [45]. As a result, there may be direct, indirect, and two types of illusory correlations between the x and y variables [46]. The Hsiao test is based on three different hypotheses, H1, H2, and H3. According to these assumptions, the H1 hypothesis asserts that the coefficients are homogeneous, whereas the alternative hypothesis asserts that they are heterogeneous. The H2 hypothesis, on the other hand, is identical to the H1 hypothesis in that it defends homogeneity while claiming that its alternative is heterogeneous. However, unlike other hypotheses, the H3 hypothesis assumes that its alternative is partially heterogeneous [43].

Table 4 shows the homogeneity test hypotheses and results for the volume of containers handled in the study and the labor force in the total population.

Table 4 shows that Hsiao, based on homogeneity, was rejected at the 1% and 5% significance levels in all three hypotheses. The H1 and H2 hypotheses are rejected because the p-values are less than 0.05, and the alternative hypothesis, heterogeneity, is accepted. Furthermore, partial heterogeneity is accepted because the p-value for partial homogeneity, which is the H3 hypothesis, is less than 0.05. It is concluded in this context that the coefficients are heterogeneous.

4.3. Second Generation Panel Unit Root Test Results

When determining cross-sectional independence in panel data analysis, first-generation unit root tests can be used, but second-generation panel unit root tests produce more accurate results, as shown in Table 4, due to the cross-sectional dependence in this study's data. Furthermore, due to globalization, country import and export volumes have increased by all modes of transportation, particularly

Table 3. *Number of labor force in the total population-horizontal sectional dependency test results*

Test	Statistic	d.f.	Prob.
Breusch-Pagan LM	45.86068	6	0.0000
Pesaran scaled LM	11.50679		0.0000
Bias-corrected scaled LM	11.40679		0.0000
Pesaran CD	3.283967		0.0010

Table 4. *Homogeneity test results*

Hypotheses	F-Stat	p-value
H1	1899.984	1.22E-80
H2	38.98734	2.31E-15
H3	1539.772	5.83E-70
H1: p=1.22E-80 <0.05 Heterogeneous H2: p=2.31E-15 <0.05 Heterogeneous H3: 2.31E-15 <0.05 Partially heterogeneous		

by sea between countries and continents and by combined transportation. As a result, the reliance on the horizontal sections that comprise the panel must be considered. Therefore, the CADF (cross-sectional augmented Dickey-Fuller) test, a second-generation panel unit root test developed by Pesaran [47], was used. This test takes into account the series' cross-sectional dependence [48].

The unit root test shown in Table 5 was performed at a level and constant for each series, and the results showed that the variables were stationary. Next, the cointegration test was used to examine the long-term relationship after determining that the variables are stationary.

4.4. Westerlund Panel Cointegration Test Results

Because of the cross-sectional dependence, the Westerlund panel cointegration test was used to test the cointegration between the variables, and the results are shown in Table 6.

According to the Robuts p-values in Table 6, there is no long-term relationship between the variables related to the volume of containers and the level of individual labor force participation in the total population because the null hypothesis of "no cointegration relationship" could not be rejected at the 1%, 5%, and 10% significance levels for all group and panel statistics. Therefore, it was determined that no equilibrium relationship existed.

4.5. Panel Causality Test Results

Because there was no cointegration relationship between the variables, the Dumitrescu-Hurlin causality test was used to determine whether there was a short-term causality relationship between them. As shown in Table 7, the delta homogeneity test was used as a secondary homogeneity test for this purpose [42].

The delta homogeneity test's significance is rejected at the 5% level, and the units are heterogeneous. Therefore, the Dumitrescu and Hurlin [36] causality test, as shown in Table 8, can be used in this case.

According to the results in Table 8, the volume of containers is the Granger cause of the labor force, and the labor force is the Granger cause of the volume of containers. As a result, bidirectional causality exists. Therefore, the result can be expressed as "volume of containers ↔ level of labor

Table 5. *Pesaran CADF second-generation panel unit root test results for volume of containers variable*

	t-bar	cv10	cv5	cv1
Container volume - 1st difference	2.610	-2.210	-2.340	-2.600
Number of labor force - 1st difference	2.610	-2.210	-2.330	-2.570
Container volume-level	2.610	-2.210	-2.330	-2.570
Number of labor force-level	2.610	-2.210	-2.330	-2.570

Table 6. *Westerlund panel cointegration test results*

Statistic	Value	Z value	p-value	Robust p-value
Gt	-0.916	0.116	0.546	0.480
Ga	-1.911	0.832	0.797	0.630
Pt	-1.810	0.676	0.250	0.400
Pa	-1.885	0.593	0.277	0.360
Note: The Bootstrap loop is 400 pieces. Latency and leading are set as 1				

Table 7. *Delta homogeneity test*

Delta	p-value
9.474	0.000
Adj.10.233	0.000
H0: Slope coefficients are homogenous	

Table 8. *Results of the Dumitrescu and Hurlin [36] causality test*

Null Hypothesis:	W-Stat.	Zbar-Stat.	Prob.
CONTAINER VOLUME does not homogeneously cause Number of Labor Force	5.37493	2.20339	0.0276
NUMBER OF LABOR FORCE does not homogeneously cause Container Volume	5.37280	2.20184	0.0277
NOTE: The max lag length is taken as 2 according to the AIC information criterion			

force participation”. In this context, it can be stated that historical data on the variable related to container volume has a significant effect on the variable of labor force number, and data on the variable of labor force significantly affects container volume.

5. Conclusions

Maritime transport, which accounts for approximately 80% of global freight transport and is the preferred mode of transport compared to other modes, is growing in importance in national economies. An example of this is the negative impact on supply chains and the global economy caused by the Suez Canal blockage due to a recent container ship stranding. In this context, as bulk and dry cargo transportation has given way to container transportation, the Mediterranean Basin, which includes Türkiye, has grown in importance as one of the most competitive trade areas. Container trade has an impact on the Mediterranean Basin’s economic balance because it has an impact on macroeconomic variables. This study attempted to determine whether there is a cointegration relationship between the “volume of containers handled” of Türkiye, Greece, Italy, and Spain, which have an active role in international container lines, and the “the labor force in total population,” which is one of the macroeconomic variables, between 2000 and 2020. Based on the findings, the causality between the volume of containers handled in the maritime sector and the level of labor force participation was assessed.

The panel data analysis method was used in this study. Panel data analysis examines cross-sectional data from a specific period and time series. It contains distinguishing features of the same units and allows them to be controlled and measured. In addition, more comprehensive studies can be conducted because it combines cross-sectional and time series data. To achieve the study’s goal, data on the volume of containers handled in TEUs between 2000 and 2020 were obtained from OECD [31] and labor force from WB [32] websites.

The Stata and EViews software packages were used to test the hypotheses. The hypotheses were tested using the Westerlund panel cointegration test and the Dumitrescu and Hurlin [36] causality test. The Westerlund test was used because it takes into account structural break and cross-sectional dependence. Because it is an adapted version of the Granger [37] causality test for heterogeneous panel data analysis, the Dumitrescu and Hurlin [36] test was also chosen. Because the cointegration relationship between the variables was not found, the Dumitrescu and Hurlin [36] causality test was used to determine whether there was a short-term causality relationship between the variables.

According to the Westerlund panel cointegration test results, there was no long-term equilibrium relationship between the volume of containers handled and the variables related to the level of individual labor force participation in the total population when the study’s findings were examined. According to the Dumitrescu and Hurlin [36] causality test, the labor force variable is the Granger cause of the volume of containers variable, and the volume of containers variable is the Granger cause of the labor force variables. The obtained result is bidirectional causality, expressed as “volume of containers ↔ level of labor force participation.” In this context, the variable related to container volume has a significant effect on the variable of labor force level, and the data of the variable of labor force level has a significant effect on container volume.

The study found that, while there is no long-term cointegration relationship between the volume of containers handled and labor force participation, there is a bidirectional Granger [37] causality relationship. According to the findings, all sectors respond to changes in a country’s economy and trade volume as a contraction or increase in capacity in the short term. In this context, it is believed that there is a relationship between the volume of containers handled and labor force participation. A larger data set should be used to examine long-term impacts. Simultaneously, it is assumed that in the short term, the level of labor force participation in sectors such as textiles, electronic goods, and pharmaceuticals, whose cargoes are mostly transported by containers, has changed or the volume of containers has changed with the change in the level of labor force participation in these sectors. These findings overlap with those of Bottasso et al. [1], Michael et al. [6], Dördüncü [22], and Tunalı and Akarçay [24]. As a result, the study’s findings are consistent. A larger data set should be used to examine long-term impacts. In this regard, all types of cargo transported by sea, as well as the product and service production areas where they are used, can be examined, and an evaluation for the related sectors can be made. This study examines the role of container transportation in trade and its effects on a country’s labor force participation rate. In future studies, Türkiye’s regional competitors can be compared by comparing maritime transport data based on countries and foreign trade data based on inflation, national income, unemployment, and sectors, using panel data analysis in the maritime sector. Türkiye’s potential weaknesses can be assessed based on the comparison results, and policies to improve these aspects can be proposed.

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