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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.

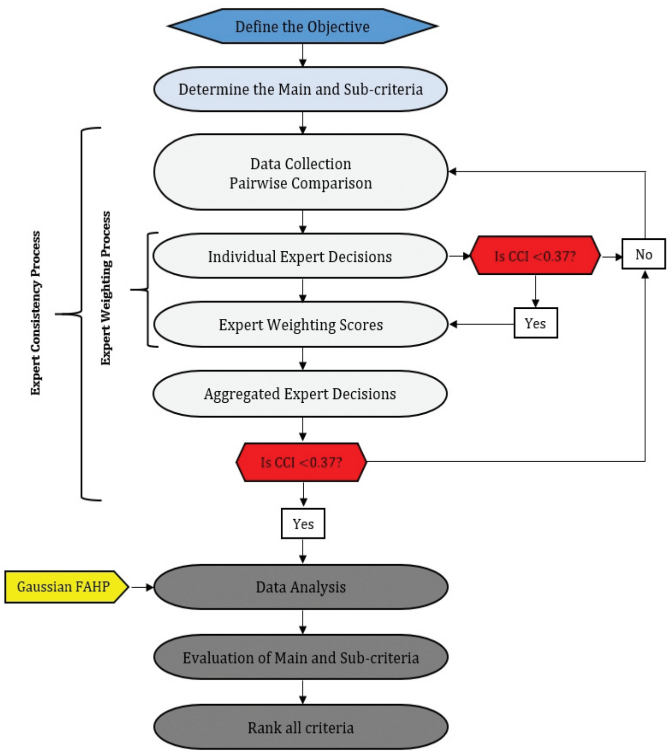

Figure 1. *Solution methodology for the study*

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:

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

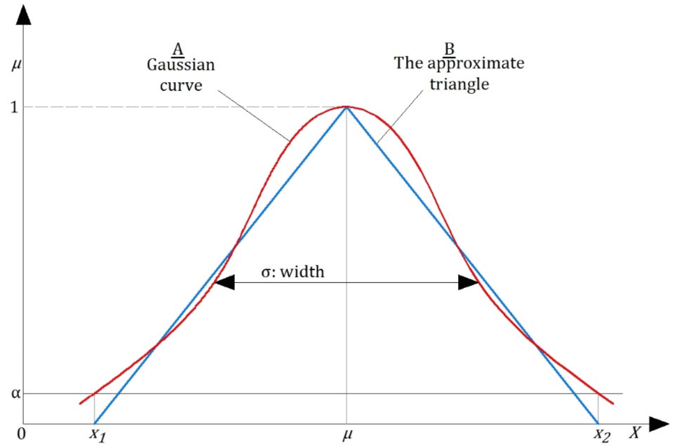

Figure 2. *Gaussian (A) and the approximate triangle (B) curves*

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

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

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

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

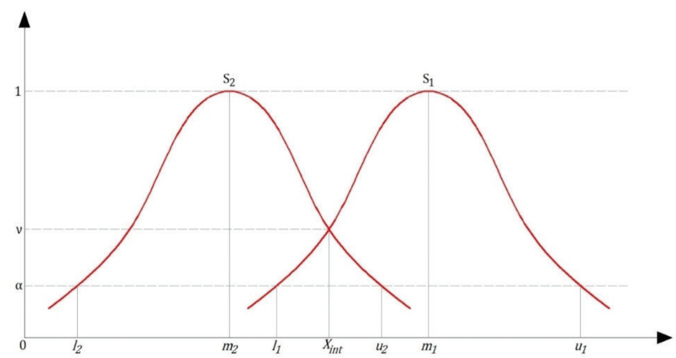

Figure 3. *Intersection of two Gaussian functions*

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

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

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:

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

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

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

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

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

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

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:

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

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

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:

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

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:

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

and

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

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

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

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

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

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

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:

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

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

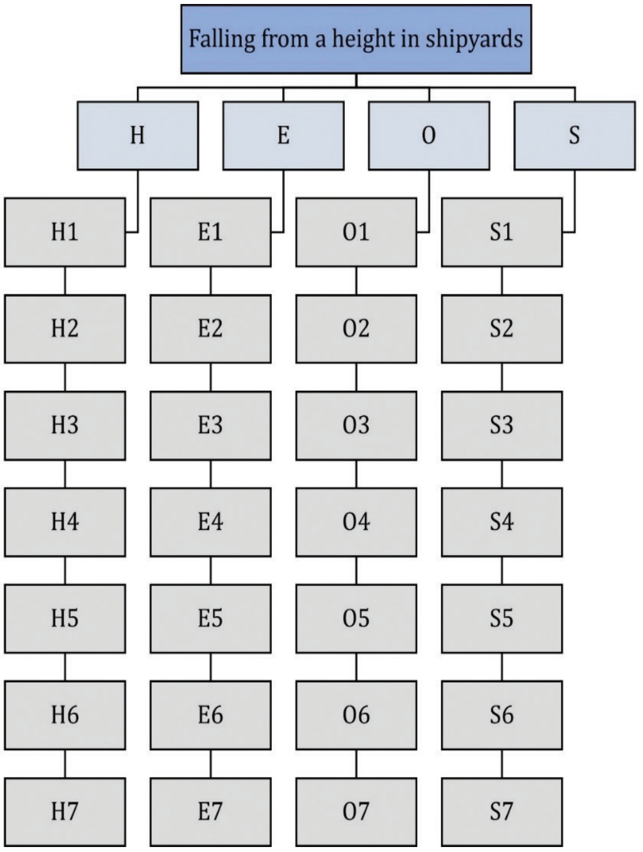

Figure 4. *Hierarchical design of the causes of falls in shipyards*

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%.

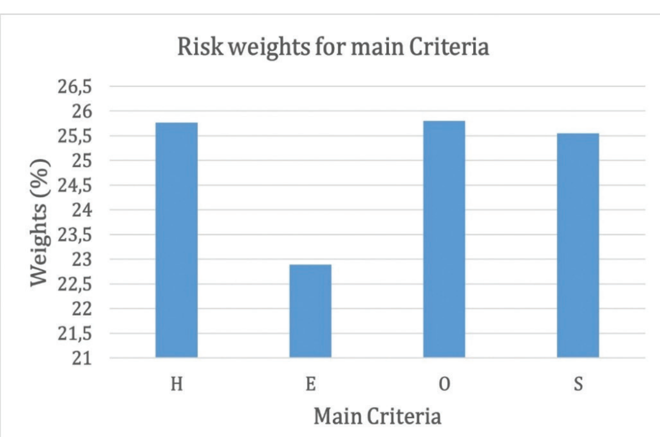

***Figure 5.** Risk values for main criteria*

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

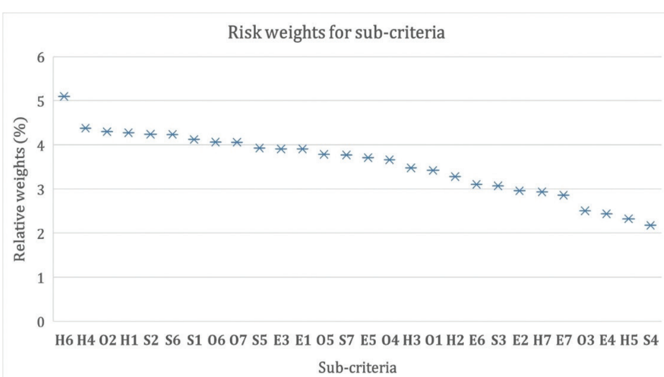

***Figure 6.** Risk values for sub-criteria*

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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