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Analysis and Management of Human-Based Risks in Ship Operations with Fuzzy FMEA and Fuzzy DEMATEL Methods

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ABSTRACT

The operations carried out on ships, which bear most of the world trade load and constitute the fundamental element of maritime commerce, involve many risks. In today's context, the concept of risk has evolved into the assessment of risk, and various methods have been developed to reduce or eliminate risks. In this perspective, the objective of the study is to identify and assess human errors, a major risk factor in accidents occurring in ship operations, through an integrated fuzzy approach, and manage them accordingly. By emphasizing the inherent risk in the nature of the human factor in maritime operations, this study makes a noteworthy contribution to maritime literature by identifying human-based risk factors using Fuzzy FMEA and Fuzzy DEMATEL methods. Although FMEA and DEMATEL methods are widely used in risk assessment in literature, there are limited number of research integrating Fuzzy Logic into these methods. Therefore, this study holds importance in presenting human-based risk factors through two different methods and highlighting the impact of the human factor in ship operations, which inherently involve risks.

1 Introduction

The majority of global trade is carried out via maritime routes. Maritime transportation plays a critical role in global trade, with over 80% of world trade volume being carried by sea. Period following Covid-19 pandemic, geopolitical changes on world maritime trade routes, situations arising from Russia's invasion of Ukraine in the Black Sea in February 2022, the insecure environment in the Red Sea and Eastern Mediterranean after Hamas's attack on Israel in October 2023, and additional events such as the Yemeni Houthis' attacks on maritime trade fleets in the Red Sea have posed challenges to maritime trade and the global supply chain. Despite these obstacles, research by the United Nations Conference on Trade and Development (UNCTAD) anticipate an average growth of approximately 2% in global maritime trade and around 3% in container shipping until the year 2028.

Thus, United States of America (USA) and the People's Republic of China (PRC) are two largest economies which have highest gross domestic product (GDP) [1]. Maritime transportation, which plays an important role in world trade, has an important place also for those countries. In the realm of container transportation, it not only manages 70% of the USA's international trade but is also crucial for the imports of the People's Republic of China. [2]. The improvement and development of ship operations, which are the main elements of maritime trade, hold significant importance for world trade. These efforts involve many studies aimed at understanding and preventing existing risks in the process.

Ships are the main arteries of maritime transportation, which is the lifeblood of the world supply chain. Regardless of whether they are at sea or in port, ships operate under constant risk. This situation implies that seafarers working on ships are continuously exposed to risks that can negatively impact their safety[3]. Indeed, between 1883 and 1892 in the British merchant fleet, the number of work-related deaths was six times higher than underground miners, nine times higher than railway workers, and 146 times higher than factory and workshop workers [4]. In another study examining 100 accidents that occurred on ships, which hold such crucial importance in the world supply chain, between 1982 and 1985, it was found that out of a grandtotal of 2250 factors contributing to the accidents, 345 were attributed to human errors. It was determined that detecting human errors before they occur is not an easy task [5]. If we look at recent history it was reported that between 2014 and 2022 23,814 casualties and incidents occurred and 604 fatalities seemed during that period. "Human factor" is also indicated as a main cause [6]. The complexity of ship operations, which involve high-risk tasks such as navigation, mooring, anchoring, and cargo handling, necessitates robust risk assessment methodologies to mitigate human-induced risks.

Seafarers frequently encounter incidents and situations with unique characteristics not commonly found in other professions. Even in the simplest adverse weather conditions, experienced by almost all mariners, the risk of accidents affecting the ship and potentially occurring on the deck increases [7]. Accurate and effective risk analysis is mandatory for the safety of life and property. In addition, it is necessity to prevent potential accidents in order to have sustainable maritime operations.

As part of the safety of global trade and the sustainability of the supply chain, it is a global necessity to assess, reduce, or eliminate the existing risks in operations on ships, which are the main elements of maritime trade. In this vein, the objective of the research is to reveal the interaction between the human based risk factors in ship operations and conducting risk analysis by integrated fuzzy methods on them. In this regard, awareness to human-based risks can be raised and time, cost and safety can be improved. When reviewing the literature, it is observed that human errors are extensively studied. Some of these researches are in health sector [8-12], manufacturing sector [13-14] and in ship operations [15-24]. The maritime industry has long sought to minimize human errors through various safety management approaches. Traditional risk assessment techniques, such as Failure Mode and Effects Analysis (FMEA) and Decision-Making Trial and Evaluation Laboratory (DEMATEL), have been widely employed in risk evaluation. However, conventional FMEA and DEMATEL methods often fail to account for uncertainty and vagueness in expert evaluations, leading to potential biases in risk prioritization. To address this limitation, fuzzy logic-based approaches have been integrated into these methods, enhancing their effectiveness in handling linguistic and imprecise data.

In recent years, several studies have explored the application of fuzzy methodologies in maritime risk assessment. Notably, previous research has focused on human error prediction in ship navigation, cargo handling, and emergency response procedures. However, there remains a gap in the literature regarding the integration of Fuzzy FMEA and Fuzzy DEMATEL for systematically evaluating human-based risks in ship operations. This study aims to fill this gap by developing a hybrid fuzzy risk assessment model to identify and analyze human-induced risks in maritime operations.

The primary objectives of this research are as follows:

- To identify the most critical human-related risk factors in ship operations.
- To apply Fuzzy FMEA for prioritizing risk factors based on their severity, occurrence, and detectability.
- To utilize Fuzzy DEMATEL to determine the causal relationships between risk factors and classify them into "cause" and "effect" categories.
- To provide strategic recommendations for improving safety measures in maritime operations based on the findings.

By integrating Fuzzy FMEA and Fuzzy DEMATEL, this study contributes to the maritime safety literature by offering a more robust and systematic approach to assessing human-based risks in ship operations. The findings are expected to assist policymakers, shipping companies, and maritime safety authorities in enhancing risk management frameworks and reducing human error-related incidents at sea.

2 Literature Review

2.1 Ship Operations and Human-Based Risks

Ships, the extensions of maritime enterprises at sea, perform their tasks by navigating under hazardous weather and sea conditions and engaging in loading and unloading operations that require precise stability calculations, as well as risky maneuvers like anchoring, mooring, and embarking operations. Despite benefiting from various electronic navigation aids during navigation activities, their automation capability is not yet advanced enough to eliminate the human factor entirely. This situation is evident when looking at the existing regulations, rules, and laws in the maritime sector, where the fundamental role of humans in activities is still acknowledged [25]. Modern-day seafarers are abidingly required to make decisions that can directly impact human, material, and environmental safety in the activities they perform. They must take these decisions in a manner that minimizes harm and ensure the correct implementation or enforcement of their decisions [26]. The human factor is a multifaceted and complex phenomenon that operates in various ways in maritime activities, involving personnel on ships and all types of coastal facility workers [27]. This situation necessitates considering the human error factor in all these risky activities. In ship operations, activities such as anchoring, mooring, embarking, narrow water and canal passages, navigation under low visibility conditions, fuel transfer, cargo handling, personnel transfer, which can be specifically defined as delicate maneuvers, are directly under the initiative and control of the human factor. These activities pose a high risk of human errors. Failures in these areas can directly impact factors critical to the fundamental mission of maritime transportation, which is the safe conveyance of cargo from one place to another.

In other words, one of the crucial requirements for the successful and safe operation of maritime trade is to ensure the stability and strength of the ship, particularly during the most critical parts of the ship operations process, such as cargo handling, by taking necessary precautions [28]. The handling of a container cargo involves a series of sequential and coordinated activities that are risky and require coordination not only among ship personnel but also between ship personnel and shore personnel [17]. Handling operations pose significant risks, including personnel injuries or fatalities, damage to cargo or transport equipment, and even the risk of capsizing the ship by disrupting its stability. Within this process, the most critical factor is the human element, presenting the highest level of risk.

30 years ago, more than 200 ships were lost annually due to accidents and casualties. But if we look at the past 10 years, the total number is recorded as only 807, furthermore in 2022, it is observed to be just 38 [29]. One of the most prominent factors underlying this situation is technological advancements. However, despite advancements in technology, understanding and mitigating human errors at sea also play a crucial role. This is because every maritime activity is centered around human presence, regardless of the developments in technology. Additionally, in 2022, at least 8 accidents were reported due to adverse weather conditions. In fact, even in these accidents, the human factor is the most crucial element. Maritime operations require a high level of foresight and awareness. Seafarers should continuously monitor themselves, their surroundings, and nature, anticipating and mitigating crises before they occur, and striving to minimize risks. Therefore, in every activity performed, human contribution and influence are the most significant factors. In the research conducted by Sampson et al. [30], the causes of 693 accidents that occurred between 2002 and 2016, it reveals that more than 85% of the reasons were attributed to human errors [30]. The importance of maritime transportation in global trade and one of the requirements for the safe, secure, and successful execution of such transportation is the analysis of risks stemming from human errors. By use of 14 years of ship accident records in the Fujian region of China, it was determined through multinomial logistic modeling that human-caused accidents can be categorized into three main groups: solely negligence errors, decision/operational errors and negligence combined with decision/operational errors occurring simultaneously [31]. In a study conducted on cargo ships which have autonomous capabilities in the vicinity of Wuhan, China, as part of examining human errors in the integration between humans and autonomy, data obtained revealed 16 variables through analysis using THERP (Technique for Human Error Rate Prediction) and Bayesian Network methods [32]. In order to identify the effect of lack of situational awareness among human error factors, research was conducted by analyzing 177 marine accidents experienced by 1952-2000 by means of Leximancer. As a result of the research, it was detected that 71% of human errors were caused by lack of situational awareness [16]. In another study conducted within the scope of revealing human errors that may negatively affect the fuel transfer process on ships, which is another sensitive activity with a high risk of environmental pollution, 38 factors were subjected to probability weighting using SOHRA (Shipboard Operations Human Reliability Analysis). As a result; incident of the fuel transfer pressure's initially low is stated as a highest potential risk. If we examine that incident, we will see that inadequate control was the highest risk factor that causes this situation [15]. In another research conducted by Ma et al. [17], 8 error sources were reached as a result of the hybrid application of SOHRA model, entropy weight model and TOPSIS methods to identify possible human errors in ship operations, which were conducted with 7 expert ship captains who have worked in ship organizations between 15-35 years. These human based error factors are presented below [17];

Table 1 Human Error Factors in Ship Operations

No.	Risk Factor
1	Inadequate checking
2	Operator inexperience
3	Lack of exercise
4	Lack of progress tracking
5	Absolute judgement required
6	Misperception of risk
7	Poor feedback
8	Unfamiliarity

It is noticeable that the error-causing factors identified in the research on human-induced errors in ship operations are similar in the literature.

Inadequate checking, since the activities carried out on board ships are of a continuous and repetitive nature, it may cause the personnel to miss sensitive points in the works performed due to fatigue, boredom, etc. This situation increases the risk and appears as a factor that raises the probability of accidents.

Operator inexperience; is the factor indicating that the seafarers do not have sufficient level of experience. Inexperienced seafarers are closer to make a mistake and this is another factor that increases the probability of human error.

Lack of exercise; is the factor indicating that the seafarers perform or undergo trainings in order to improve their experience, knowledge and accumulation in the activities performed, to prevent forgetting that may occur in activities that have not been performed for a long time and to improve process safety and success.

Lack of progress tracking; is a factor indicating that the seafarers lose attention and lose track of the process due to reasons such as fatigue in repetitive and time-consuming processes. Since the procedure of the ship operations requires high attention, it is another factor that effects the probability of human error.

Absolute judgement required; factor in human-based errors in ship operations refers to situations where a crew must make a precise and definitive decision without ambiguity or uncertainty. In these scenarios, the individual must accurately assess and interpret various factors and conditions to arrive at a correct judgement. The difficulty of making an absolute judgement can increase the likelihood of human error, as it often involves high levels of stress, pressure, and the need for quick decision-making, all of which can compromise the accuracy and effectiveness of the decision.

Misperception of risk; is a factor indicating errors in risk assessment by virtue of mental fatigue, mental duress, lack of time or inexperience.

Poor feedback; is a factor indicating the transfer of experience as a result of activities carried out in a way that may lead to misunderstandings.

Unfamiliarity; is a factor that is especially caused by the newly recruited ship personnel and shows the lack of acquaintance with the activities performed.

Ships are areas that contain great differences compared to other working areas. This difference, which transforms maritime into a way of life beyond being a profession, starts with the fact that the ships, which are the workplaces of seafarers, are also their living spaces. This situation reveals a condition that obliges seafarers to keep their awareness at a high level even when they are not performing activities or at rest. Even when a ship captain is resting in his cabin, he listens to the sound of the engine and follows the vibrations on the ship. Perceptions that try to be kept open 24 hours a day cause situation that lead to the formation of error factors such as fatigue and absent-mindedness after a while. These factors arising from the monotonous life order are sometimes exacerbated by the negative effects of nature, which is in a constant struggle. Seafarers are required to make risk analysis and take early preventive measures before the activities they perform in the light of all these situations.

2.2 Research on Risk Analysis

Although the modern understanding of risk dates back to the Indo-Arabic numerical system, detailed studies on the concept of risk began with the Renaissance period. The term risk derives from the Italian word “risicare”, which means to dare. Considered concordantly, risk is not an imposition but a choice [33]. In the historical process, people have attempted to take some precautions against risk. As the first step, they aimed to anticipate the risk. Risk analysis is a system created to increase awareness and foresight within the scope of errors that may occur within the processes. In this regard, risk analysis aims to create time, personnel, material and cost efficiency by foreseeing possible errors and failures that may occur within the processes. Risk analysis is an important cornerstone in this framework [34]. In this scope, risk analysis methods have been created to prevent errors / failures that may occur within the processes. Some of the most commonly used risk models are Bayesian Networks (BBN), Geometric Models, simulations, Analytical Hierarchy Process (AHP), Fuzzy Inference, Event Tree Analysis (ETA), Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA), System Theoretical Process Analysis (STPA) and Regression Analysis [35]. The purpose of these risk analysis models is to contribute to the end of the process in a healthy way, especially the safety of property and life, by increasing foresight and awareness within the processes.

Approximately 80% of accidents in maritime transportation are caused by human error. This was also demonstrated in a study conducted by Soares and Teixeira [36], which analyzed the application of the FSA method based on accidents that have occurred [36]. In another study, the research conducted by examining 214 accidents/incidents that resulted in grounding of 214 dry cargo, passenger ships and tankers over 500 Gross Tons, it was determined that 60% of marine accidents were induced by human error and 22% of these errors were caused by errors in the decision-making process [37]. In the research by Lim et al. [38], 180 maritime risk analysis studies were reviewed. The aim was to identify the need to take into account human behavior during operations and to use technology more effectively to create tighter control mechanisms. Additionally, statistical, simulation, and optimization models were created to develop more effective methods for information and data collection and to develop prevention mechanisms [38]. In a study conducted by Liv et al. [39], 87 academic studies on risk mitigation/containment in maritime transportation were analyzed through quantitative research and it was found that human errors have vital importance in risk management [39]. Numerous studies in the literature focus on assessing existing risks in the maritime sector and implementing precautionary measures. A common theme across all these studies is the recognition of humans as a highly significant factor contributing to operational risks.

3 Methodology

In the research conducted by Ma et al. [17], 8 risk factors for cargo-loading operations were identified. These factors resulted from evaluations by 7 container ship masters consulted during the research. The factors were found to have the highest risk rate for cargo-loading operations. It is aimed to study with different specialized experiences in ships for our work to comprise general. So, in our study, first of all the human-based risk factors for ship operations discussed in detail by 4 experts using face-to-face interview. After achieving a consensus on the risk factors, we observed that they are very parallel with Ma et al. [17] factors. So, experts decided to continue their analysis with same 8 factors. These 4 experts are chosen because of their long serving times at sea in different positions which reached oceangoing master and also for different types of ship types they served. 2 of the experts have served and are serving on board for more than 10 years in research vessels and general cargo ships, 1 for between 20-40 years in bulk carriers and 1 for more than 40 years in tankers. All of them have undertaken the responsibility of all operations carried out within their specialized operations due to their ships as an oceangoing master. 2 of the experts are over 70 years old and the other 2 are 35 and 36 years old. All of the experts whose opinions were consulted within the scope of the research are male and their nationalities are Turkish. During face-to-face interview, authors only explained the details of the methodology and described the details of the factors. After the consensus on the 8 risk factors Ma et al. [17] revealed, each expert evaluated the factors individually. Subsequently following methodologies applied to their evaluations.

The FMEA and DEMATEL methods used in the study are based on the subjective evaluations of the participants, with risk scores relying on the personal experiences and opinions of the team. Therefore, risk analysis should als o be conducted at different times by different experts. FMEA requires in-depth knowledge for identifying failure modes and assessing their effects, while DEMATEL relies on expert opinions to determine the interactions and relationships between factors. The combined use of these two methods can complicate the data collection and analysis process, making it more complex and time-consuming. DEMATEL's dependence on expert opinions can vary based on subjective evaluations, increasing the risk of misdirection, and when combined with the subjectivity constraint of FMEA, the reliability of the results may decrease. Additionally, integrating the steps and calculations required by both methods can make the analysis process unmanageable. As FMEA and DEMATEL are typically static analyses, they need continuous updates when system changes or new risks emerge, making timely and effective updates challenging in a dynamic process. Despite these limitations, the combined use of FMEA and DEMATEL can provide a deeper and more comprehensive assessment in risk analysis, highlighting the importance of being aware of these limitations and taking appropriate measures during the process [40-41].

3.1 Fuzzy Logic

Fuzzy logic is an important theory in many fields such as artificial intelligence, management science, control engineering, decision theory, computer science, expert systems, logic, process analysis, pattern recognition and robotics. Until Fuzzy Logic, we had a structure based on imposing approaches to decision-making or computational arguments, more precisely on yes-no, true-false distinctions. But with the help of Fuzzy Logic, the differences in relative linguistic concepts have been mathematized and made sense of in a matrix [42]. Fuzzy logic makes it possible to analyze people's past experiences and knowledge by standardizing the uncertainties of human thoughts and linguistic expressions in the decision-making process [43]. Fuzzy logic has become one of the most important instruments of quantitative research methodology today thanks to its feature.

In other words, fuzzy logic used for a more subjective use of uncertainty in human self-evaluations [44]. Within the research, the data collected from the experts within the scope of FMEA and DEMATEL methods were fuzzified and the importance weight degrees were obtained through the fuzzified values of the Fuzzy Risk Priority Number (*FRPN*) within the scope of Fuzzy FMEA. Besides factor-relationship table calculated with Fuzzy DEMATEL to reveal how these factors are effecting each other. Fig. 1 shows the modeling of the Fuzzy FMEA method.

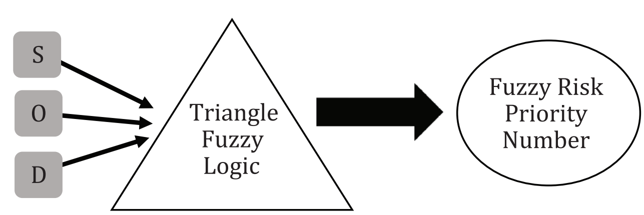


Figure 1 Fuzzy Logic Model

The stages of the process of applying triangular fuzzy logic to the raw data collected by the experts are presented below. Fig. 2 indicates the triangular fuzzy numbers. Triangular fuzzy numbers (a_1, a_2, a_3) are represented. a_1, a_2 and a_3 symbolize the minimum, middle and maximum values [45]. Triangular fuzzy logic chosen duty it's high capability of describing uncertain knowledges, easy modelling and sufficient sensitivity characteristics [46]. In this research, mathematical process applied by Lin (2006), followed during the fuzzy logic process [47].

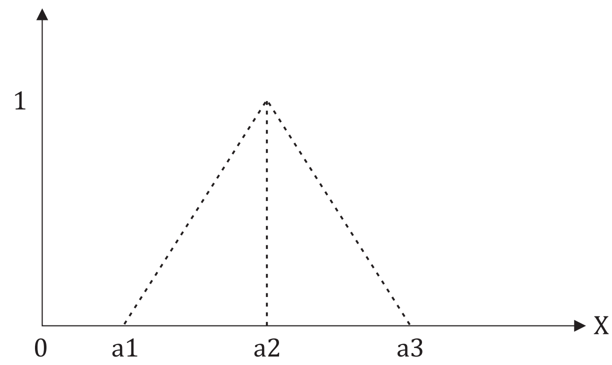


Figure 2 Triangular Fuzzy Numbers

Triangular fuzzy number set can formulate as follows. It composes of 3 set of numbers.

$$f_{\tilde{A}}(x) = \begin{Bmatrix} 0, & x < a_1 \\ \frac{(x-a_1)}{(a_2-a_1)}, & a_1 \le x \le a_2, \\ \frac{(a_3-x)}{(a_3-a_2)}, & a_2 \le x \le a_3, \\ 0, & x > a_3 \end{Bmatrix} \tag{1}$$

If $\tilde{A}$ and $\tilde{B}$ is two parameterized numbers of triangular fuzzy number set, their mathematical rules should be as followed.

$$\begin{aligned} \tilde{A} + \tilde{B} &= (a_1,\ a_2,\ a_3) + (b_1,\ b_2,\ b_3) = \\ &= (a_1 + b_1,\ a_2 + b_2,\ a_3 + b_3) \\ \tilde{A} - \tilde{B} &= (a_1,\ a_2,\ a_3) - (b_1,\ b_2,\ b_3) = \\ &= (a_1 - b_1,\ a_2 - b_2,\ a_3 - b_3) \\ \tilde{A} * \tilde{B} &= (a_1,\ a_2,\ a_3) * (b_1,\ b_2,\ b_3) = \\ &= (a_1 b_1,\ a_2 b_2,\ a_3 b_3) \\ \tilde{A} / \tilde{B} &= (a_1,\ a_2,\ a_3) / (b_1, b_2, b_3) = \\ &= (a_1/b_1, a_2/b_2, a_3/b_3) \end{aligned} \tag{2}$$

The agreement of group members on subject is import part of achieving the optimal solution. For that we are using triangle fuzzy numbers sets and to decide the left and right numbers of it we need to calculate the weight as follows.

$$\tilde{\omega}_{ij}^{k} = \left(a_{1ij}^{k},\ a_{2ij}^{k},\ a_{3ij}^{k}\right) \tag{3}$$

Clarification;

$$\begin{aligned} xa_{1ij}^{k} &= (a_{1ij}^{k} - \min a_{1ij}^{k})/\Delta_{min}^{max} \\ xa_{2ij}^{k} &= (a_{2ij}^{k} - \min a_{2ij}^{k})/\Delta_{min}^{max} \\ xa_{3ij}^{k} &= (a_{3ij}^{k} - \min a_{3ij}^{k})/\Delta_{min}^{max} \end{aligned} \tag{4}$$

If, $\Delta_{min}^{max} = \max r_{ij}^{n} - \min l_{ij}^{n}$ left (ls) and right (rs) stagnation values;

$$\begin{aligned} xls_{ij}^{k} &= xa_{2ij}^{k}/(1 + xa_{2ij}^{k} - xa_{1ij}^{k}) \\ xls_{ij}^{k} &= xa_{3ij}^{k}/(1 + xa_{3ij}^{k} - xa_{2ij}^{k}) \end{aligned} \tag{5}$$

Crisp values;

$$\begin{aligned} x_{ij}^{k} &= \frac{\left[xls_{ij}^{k}\left(1 - xls_{ij}^{k}\right) + xrs_{ij}^{k} \times xrs_{ij}^{n}\right]}{(1 - xls_{ij}^{k} + xrs_{ij}^{k})} \\ \tilde{\omega}_{ij}^{k} &= min a_{ij}^{n} + x_{ij}^{n} \Delta_{min}^{max} \end{aligned} \tag{6}$$

Integration of surveys conducted by k experts;

$$\tilde{\omega}_{ij}^{k} = 1/k(\tilde{\omega}_{ij}^{1} + \tilde{\omega}_{ij}^{2} + \cdots + \tilde{\omega}_{ij}^{k}) \tag{7}$$

3.2 Failure Modes and Effects Analysis (FMEA)

In the context of the increasingly important application of risk analysis modeling in today's world, FMEA which is implemented to this research is a risk analysis modality that is compatible with many engineering and reliability measurement methods. It enables the evaluation of risk levels, predicting potential errors/failures in advance, and prioritizing them by revealing the frequency levels [48]. Three basic values constitute the FMEA method. These are Occurrence (*O*), Severity (*S*) and Detection (*D*). Those values help us to reach the Risk Priority Number (*RPN*). *RPN* is key value that prioritizes the risk in the situation it applies [49].

Constituent parts of factors that generate *RPN* are shown in Table 2 *RPN* is the prioritization reference value obtained as a result of multiplying these three components with each other.

Table 2 RPN creating factors in FMEA [50-52]

Degree	S	O	D
10	Severe	Almost Certain	Like it's not possible
9			Unlikely
8	Major	Likely	Slightly Unlikely
7			
6	Significant	Possible	Possible
5			Somewhat Possible
4	Moderate		Likely
3		Unlikely	Highly Likely
2	Minor		Very Likely
1	Negligible	Rare	Almost Certain

$$RPN = S \text{ x } O \text{ x } D \tag{8}$$

The criteria in Table 3, Table 4 and Table 5 presented below are used for the value analysis of the factors that generate the *RPN*. Table 3 shows the probability of failure value and ratio for the probability factor.

Table 3 FMEA Probability Value Table [51-52].

Occurance	Value	Ratio
Rare	1	≤1/1.500.000
Unlikely	2	1/150.000
	3	1/15.000
Possible	4	1/2.000
	5	1/400
	6	1/80
Likely	7	1/20
	8	1/8
Almost Certain	9	1/3
	10	>1/2

Table 4 shows the impact status, value, and criteria of the error for the severity factor. As the effect intensity increases, the *RPN* value will grow in direct proportion.

Table 4 Unique Severity Rating Table

Severity	Criterion	Degree
Severe	It may cause the ship to capsize or cause considerable damage. It is possible to cause death or dangerous injury to employees.	10
		9
Major	There is a possibility of life-threatening or injury to employees.	8
		7
Significant	It is possible to create a health and safety problem.	6
		5
Moderate	There are no health and safety problems. A number of disruptions may occur in the operation of the process.	4
		3
Minor	Insignificant disruptions may occur in the operation of the process.	2
Negligible	It does not cause any negative effects	1

Table 5 shows the error discoverability status, value and criteria for the detection factor. An uptrend in the detection factor value connote that the discoverability is harder. Eventually, it'll cause the *RPN* to decrease.

Table 5 FMEA Detection – Deviation Value

Detection	Value	Criterion
Almost certain	1	The error is easily discovered.
Very Likely	2	The error is obvious.
Highly Likely	3	
Likely	4	
Somewhat Possible	5	
Possible	6	The error detectability is in middle degree.
Slightly Unlikely	7	
	8	
Unlikely	9	The error detectability possible with high controls.
Like it's not possible	10	The error detectability is extremely hard.

After assigning to all variables, evaluate the calculated *RPN* value within the framework of the criteria in Table 6.

Table 6 RPN Evaluation

RPN Value	Process
RPN < 40	There is no need to take precautions
40 ≤ *RPN* ≤ 100	Taking precautions will be beneficial.
RPN > 100	It is mandatory to take precautions.

3.3 Decision Making Trial and Evaluation Laboratory (DEMATEL)

DEMATEL is a structural modeling method that collects complex factors under a matrix and directional graph to show not only their relationship levels with each other but also allows importance weight rating [43]. DEMATEL is a model, which has a wide spectrum of uses, that enables the detection of not only the direct effects of complex problem factors but also the factors that affect them indirectly [54]. In this research, DEMATEL was used to uncover the relationships between the factors that constitute human-based risks in ship operations. The importance and weight levels of these factors were determined. This effort aimed to provide data for making informed decisions in the risk reduction phase. Fuzzy logic integrated to DEMATEL to succeed more accurate result. Fuzzy DEMATEL process steps are conducted as in Fig. 3 [54-56].

For this purpose, the DEMATEL factor-relationship tables were filled in by the experts during the semi-structured interviews within the criteria in Table 7. Experts filled these tables individually without prejudice.

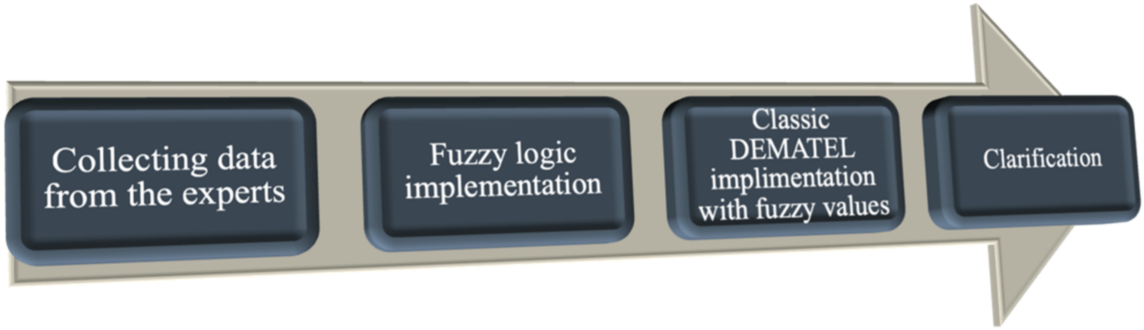


Figure 3 Fuzzy DEMATEL process model

Table 7 DEMATEL Factor-Impact Rating Table

Impact	Degree
No effect	0
Very weak effecty	1
Weak effect	2
Moderate effect	3
Strong effect	4

4 Results

Severity, Occurrence and Detection values of 8 risk factors were determined by the experts based on their own experience. These values were subjected to the Fuzzy FMEA process series and the following values were obtained.

If we compare the results presented in Table 8 with Table 6;

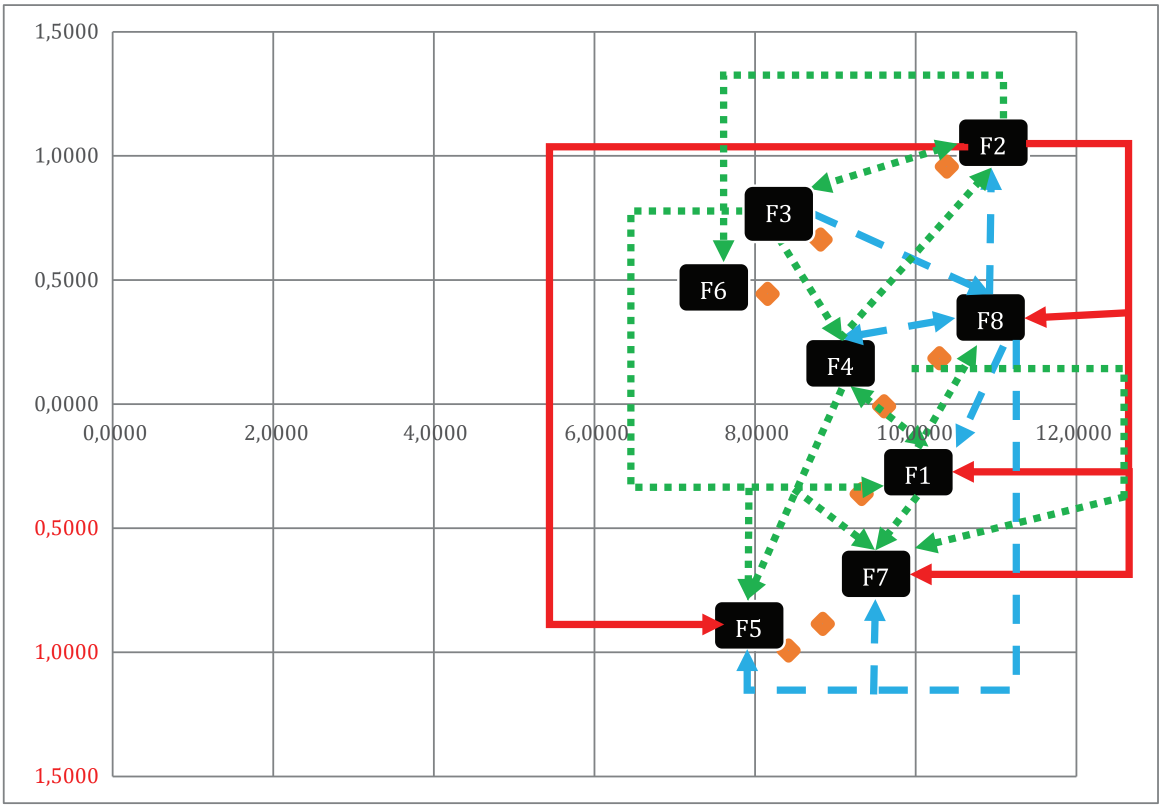
- Risk factors which taking precaution is mandatory; *F5, F4, F1, F6.*
- Risk factors which taking precaution is beneficial; *F2, F7, F3*.
- Risk factors which taking precaution is not necessary; *F8*.

When *F8*, which emerges alone as a risk factor that does not require any precautions, is observed, although there is no significant variation in the average values of other risk factors in terms of impact and probability factors, the fact that it is easily detectable emerges as the reason that prevents this factor from posing a significant risk. As a matter of fact, *F8* has the lowest detectability value with 1.25. *F5* has the highest *FRPN* value as a result of fuzzy FMEA and has the most important priority in the categories that need to be taken precautions, as well as the highest impact value with 9 points and the highest recognizability value with 6.25 points. The factor with the highest probability of occurrence is *F4* with 6.75 points.

Fuzzy DEMATEL results acquired due to the experts' elobrations presented in Graph 1. In Graph 1; red lines represents strong, green lines represents mideum and blue lines represents weak relations between factors.

Table 8 Fuzzy FMEA Results

Factor No.	Risk Factor	*Fuzzy S*	*Fuzzy O*	*Fuzzy D*	*FRPN*
F1	Inadequate checking	7.25	6.50	5.00	**235.63**
F2	Operator inexperience	5.75	4.75	2.75	**75.11**
F3	Lack of exercise	5.75	4.50	2.25	**58.22**
F4	Lack of progress tracking	7.00	6.75	5.25	**248.06**
F5	Absolute judgment required	9.00	4.50	6.25	**253.13**
F6	Misperception of risk	8.00	4.75	4.75	**180.50**
F7	Poor feedback	4.75	4.50	3.00	64.13
F8	Unfamiliarity	4.25	4.50	1.25	**23.91**



Graph 1 FDEMATEL Factor-Relationship

According to Graph 1;

- *F1* have WEAK relationship with only *F4, F7* and *F8*. Besides, there is no relationship with any other factor.
- There is a STRONG relationship between *F2* and *F1, F4, F5* and *F8*, and a MIDEUM relationship with *F3* and *F6*. Thus, it is seen that *F2* affects all other factors.
- There is a MEDIUM relationship between *F3* and *F8*, and a WEAK relationship with *F1, F2, F4, F5* and *F7*. There is no relationship between *F3* and *F6*.
- There is a MEDIUM relationship between *F4* and *F8*, and a WEAK relationship with *F1, F2, F5* and *F7*. There is no relationship between *F4* and *F3* and *F6*.
- *F5, F6* and *F7* have no effect on any other factor.
- There is a MEDIUM relationship between *F8* and *F1, F2, F4, F5* and *F7*.
- Except for *F2*, none of the factors has an effect on all other factors.

According to Table 9, which shows the importance weights of the risk factors calculated by Fuzzy DEMATEL, it is seen that the factor with the highest importance weight is *F2*. The other factors are *F2, F8, F4, F1, F7, F3, F5* and *F6* respectively.

Table 9 FDEMATEL Importance Weight Rating (IWR)

Factor	IWR
F1	0.1261
F2	0.1409
F3	0.1194
F4	0.1297
F5	0.1145
F6	0.1103
F7	0.1200
F8	0.1391

5 Discussion

It is imperative to conduct risk assessments within the scope of foreseeing the existing risks and taking measures in ship operations, which are the cornerstone of maritime transportation, which is the locomotive of the world supply chain. As a matter of fact, the primary purpose of this study is to redound to the evaluation of the existing risks in ship operations and to take measures. In this context, the aim is to raise awareness, primarily among seafarers and all units that contribute directly or indirectly to ship operations, and to contribute to the improvement of time, cost, and safety.

In this study, firstly, the literature was reviewed to identify other studies on the subject and it was determined that 8 risk factors were identified as a result of Ma et al. [17] based on 7 expert opinions. The 8 factors were prioritized by Fuzzy FMEA method and the relationships between the factors were determined and importance weighting was done by using Fuzzy DEMATEL method for the research.

In research by Mišković et al. [24] inadequate training considered as a main human based factor that indicates risk in ship operations. However, inadequate training is explained by authors as unfamiliarity, lack of exercise and inexperience. This similarity supports factors chosen for this study. As a result of the fuzzy FMEA method, it is seen that major factor causing human error in ship operations is Inadequate Control (*F1*). In the study conducted by Ma et al. [17], this factor is also stated as the most common failure factors for cargo-loading operations. Also the research published by Akyüz et al. [15]; most probable risk factor is keeping the fuel flow pressure low at the beginning. This is due to the ineffective use of the control mechanism in the process, which is considered to be supportive of the verity of this study. In the previous study conducted by Grech et al. [16], the primary human error factor identified was a lack of situational awareness. This lack of situational awareness is directly related to inadequate control. This is another example that supports our research.

The main reason for this similarity in both studies is the environment in which ship operations take place. The biggest challenge that seafarers face in their activities is the one with nature. The variable structure of nature causes variable error factors in the activities carried out. For this reason, in all kinds of activities carried out by seafarers, they have to apply the control mechanism alive and effective, regardless of any variables such as the number of repetitions, time and place.

5 Conclusion

For the conclusion; operator Inexperience (*F2*), which has the highest importance weight as a result of the fuzzy DEMATEL method, stands out as the most important factor that may affect the errors of the seafarer personnel who have to continuously improve themselves in the face of constantly changing situations during the activities carried out. Learning is lifelong for seafarers. Because every changing condition in nature creates a new situation that is unique to itself and creates a new reading. In this context, operator inexperience is a factor that has a direct impact on all other factors.

Another factor with a high importance weighting, unfamiliarity (*F8*); although it has a medium impact on many other factors, it is only recommended to take precautions as it is an easy to detect error factor. *F2* and *F8* are failure factors that can be significantly contributed positively through training. In addition, since these factors are relatively easy to identify, even though they were found to be effective on many factors in fuzzy DEMATEL, the fuzzy FMEA method revealed that *F8* is in the category of recommended precautions, while *F2* is only the fifth factor to be considered.

When these two factors, which are related to education, are evaluated together with *F3*, it is seen that the quality of the education received by seafarers is high. The fact that *F2* and *F3* are the second and third most common problem factors in the research conducted by Ma et al. [17] can be explained by the quality of maritime education on a country basis.

The results of this research showed that when considering risk factors in ship operations experience and knowledge have a very important place. However, it is also easy to detect seafarers who has lack of experience or knowledge. In this regard, lack of experience and knowledge are very rare human based risk factors that seafarers face.

In the analysis of human-related risks in ship operations, the combined use of Fuzzy FMEA and Fuzzy DEMATEL methods provides more reliable outcomes in situations characterized by high uncertainty and subjectivity. Human errors and their potential consequences are often ambiguous and difficult to quantify, making fuzzy logic a suitable approach for more accurate modeling of these uncertainties. The study identifies the potential impacts of human errors, evaluating their severity, probability, and detectability. Fuzzy DEMATEL is employed to analyze the interactions and relationships of these errors with other factors within the system, thereby enhancing understanding of complex human-machine interactions in ship operations. The research findings support more effective management of human-related risks and continual improvement of operational processes. In this regard, if we look at implications of the research; Practical implications;

- Contributes positive impact on development of safety protocols in ship operations,
- Creates security culture for preventing human-based risks,
- Reveals importance of security culture and creates conversion on organization culture,
- Suggests replanning of operational processes to prevent human-based risks,
- Suggests revise on education plan of ship crew.

Theorical implications;

- Reveals human-based risks in ship operations and provides better understanding,
- Encourage new safety protocols to prevent human-based risks,
- Helps to deduce the human-based risk factors and how to prevent them.

The biggest mistakes caused by human errors in ship operations are the mistakes made in the follow-up and control stages of the activities during the execution. The most important measure to be taken to prevent this situation is to raise the awareness of the personnel. The fight against nature, which lies at the basis of maritime, requires the personnel to engage in the work with maximum attention and seriousness. In ship operations where the necessary attention is paid, there will be a significant reduction in errors induced by human errors.

It is considered that the easiest and most effective measure to be taken in this context will be the creation of checklists for the activities to be performed. If the checklists are prepared in a sufficiently detailed and purposeful manner, it will bring convenience in process follow-up and standardization in the output, regardless of the operator. However, using checklists in all types of activities will also not going to be solution always [57]. First of all, it will cause too much formalization in the organizational structure and will lead to a serious decline in the initiative skills of the personnel, especially in emergency situations.

It would be beneficial to provide theoretical trainings and courses in order to prevent this negative situation and at the same time to contribute positively to the lack of training, which is another error factor, and to improve the decision-making and initiative skills of the personnel, especially during the theoretical training in emergency scenarios.

During this study, the opinions of four oceangoing masters specialized in their profession were consulted and the evaluation was carried out based on general ship operations. Even this paper covers the general risk factors in shipping operations, this is also constituting the limitations. Because if specified operations like navigation, cargo handling etc. it can show minor differences in risk factors. In future studies, it is considered that focusing on special events such as cargo handling or safe navigation may elicit the results of the research on specified event and cumulative results to be obtained by collecting the results on different operations will be more useful. Also, another limitation for the research was our experts. Since we worked with only bulk carrier, research vessel, general cargo ship and tanker oceangoing masters, working with other kinds of ship's crew also can be useful for the next studies. Moreover, root reasons, like psychological or physical ones, for our factors can contribute positively to literature.

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