

**ANKARA YILDIRIM BEYAZIT UNIVERSITY**  
**GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES**



**AN INTEGRATION OF FUZZY MULTI-CRITERIA DECISION-  
MAKING METHODS AND RISK ANALYSIS IN THE DEFENSE  
INDUSTRY**

**M.Sc. Thesis by**

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**August, 2024**

**ANKARA**

**AN INTEGRATION OF FUZZY MULTI-CRITERIA  
DECISION-MAKING METHODS AND RISK ANALYSIS  
IN THE DEFENSE INDUSTRY**

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**by**

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## M.Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “**AN INTEGRATION OF FUZZY MULTI-CRITERIA DECISION-MAKING METHODS AND RISK ANALYSIS IN THE DEFENSE INDUSTRY**” completed by **ÖZGE DAŞDEMİR** under the supervision of **PROF. DR. ERGÜN ERASLAN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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**2024, 20 August**

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# **AN INTEGRATION OF FUZZY MULTI-CRITERIA DECISION-MAKING METHODS AND RISK ANALYSIS IN THE DEFENSE INDUSTRY**

## **ABSTRACT**

In today's business environment, companies are increasing the importance they attach to risk assessment studies to ensure occupational health and safety. Carrying out an effective risk analysis to identify and prevent existing or potential hazards in businesses is of great importance. Especially in sectors such as the Defense Industry, where strategic decisions are taken, protective and preventive measures should be taken by making risk analyses. The objective of this study is to introduce a new approach to conventional risk assessment by integrating fuzzy logic-based multi-criteria decision-making (MCDM) methods and the Fine-Kinney Method, which is one of the risk analysis methods. The parameters used in the Fine-Kinney method were evaluated within the framework of Fuzzy Logic and risk scores were found. The Fuzzy AHP method was used to weight the risk parameters (Probability, Frequency, Consequence) used in the Fine-Kinney method. Then, the Fuzzy VIKOR method was applied to prioritize hazards. Thanks to this integration, uncertainties and risks were better understood, enabling more realistic and effective decisions to be made. In addition, the methods were explained step by step and it was aimed to guide them so that they can be used in similar problems. Through the integrated utilization of fuzzy logic and risk analysis, it is possible to enhance the management of uncertainties and risks in the defense industry, leading to a more flexible and effective decision-making process.

**Keywords:** Risk Analysis, Fuzzy Logic, Fine-Kinney Method, Multi-Criteria Decision Making (MCDM), Defense Industry.

# SAVUNMA SANAYİNDE BULANIK ÇOK KRİTERLİ KARAR VERME YÖNTEMLERİ İLE RİSK ANALİZİNİN ENTEGRASYONU

## ÖZ

Günümüz iş ortamında şirketler, iş sağlığı ve güvenliğinin sağlanmasına yönelik risk değerlendirme çalışmalarına verdikleri önemi giderek artırmaktadır. İşletmelerde mevcut veya potansiyel tehlikelerin tespit edilmesi ve önlenmesi için etkin bir risk analizinin yapılması büyük önem taşımaktadır. Özellikle Savunma Sanayii gibi stratejik kararların alındığı sektörlerde risk analizleri yapılarak koruyucu ve önleyici tedbirlerin alınması gerekmektedir. Bu çalışmanın amacı, bulanık mantık tabanlı çok kriterli karar verme (MCDM) yöntemleri ile risk analizi yöntemlerinden biri olan Fine-Kinney Yöntemini entegre ederek geleneksel risk değerlendirmesine yeni bir yaklaşım getirmektir. Fine-Kinney yönteminde kullanılan parametreler Bulanık Mantık çerçevesinde değerlendirilerek risk puanları bulunmuştur. Fine-Kinney yönteminde kullanılan risk parametrelerinin (Olasılık, Frekans, Şiddet) ağırlıklandırılmasında Bulanık AHP yöntemi kullanılmıştır. Daha sonra tehlikelerin önceliklendirilmesi amacıyla Bulanık VIKOR yöntemi uygulanmıştır. Bu entegrasyon sayesinde belirsizlikler ve riskler daha iyi anlaşılabilir ve gerçekçi ve etkili kararların alınması sağlanmıştır. Ayrıca yöntemler adım adım anlatılarak benzer problemlerde kullanılabilir şekilde yol gösterilmesi amaçlanmıştır. Bulanık mantık ve risk analizinin entegre kullanımı sayesinde savunma sanayindeki belirsizliklerin ve risklerin yönetimini geliştirmek, daha esnek ve etkin karar alma sürecine ulaşmak mümkündür.

**Anahtar Kelimeler:** Risk Analizi, Bulanık Mantık, Fine-Kinney Yöntemi, Çok Kriterli Karar Verme (MCDM), Savunma Sanayii.

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## NOMENCLATURE

### Acronyms

AHP	Analytical Hierarchy Process
BWM	Best and Worst Method
CODAS	Combinable Distance Based Assessment
DMRA	Decision Matrix Risk Assessment
ETA	Event Tree Analysis
FAHP	Fuzzy Analytical Hierarchy Process
FVIKOR	Fuzzy Vise Kriterijumska Optimizacija I Kompromisno Resenje
F-SWARA	Fuzzy Step-Wise Weight Assessment Ratio Analysis
F-DEMATEL	Fuzzy Decision-Making Trial And Evaluation Laboratory
F-MABAC	Fuzzy Multi-Attributive Border Approximation Area Comparison
FTA	Fault Tree Analysis
FMEA	Failure Mode And Effect Analysis
FFS	Fermatean Fuzzy Set
HAZOP	Hazard and Operability Study
MCDM	Multi-Criteria Decision-Making
IT2FS	Interval Type-2 Fuzzy Set
IVSF	Interval-Valued Spherical Fuzzy
MULTIMOORA	Multi- Objective Optimization by Ratio Analysis
MAIRCA	Multi-Attribute Ideal Real Comparative Analysis
PFAHP	Pythagorean Fuzzy Analytic Hierarchy Process
PFCOPRAS	Pythagorean Fuzzy Complex Proportional Assessment
PFPPRA	Pythagorean Fuzzy Proportional Risk Assessment
PHA	Preliminary Hazard Analysis
RPN	Risk Priority Numbers
SWOT	Strengths, Weaknesses, Opportunities, Threats
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VIKOR	Vise Kriterijumska Optimizacija I Kompromisno Resenje

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# CHAPTER 1

## INTRODUCTION

In today's rapidly changing and uncertain world, ensuring occupational health and safety has become an increasingly important issue for enterprises. To minimize possible accidents and damages that may occur, protective and preventive measures must be taken in terms of occupational health and safety. Therefore, carrying out an effective risk analysis to identify and prevent existing or potential hazards in businesses is of great importance.

Risk analysis is the works carried out to define the dangers that may arise during the activities of companies. Risk management is of great importance, especially in sectors where risk is high and strategic decisions are taken, such as the defense industry. Effectively managing risks in this environment is critical for ensuring the safety, security, and success of defense operations. Therefore, the most effective methods to eliminate or minimize risks should be determined.

The defense industry is a high-risk sector because it involves projects of national security and strategic importance. The potential risks in this sector can have significant implications in terms of both cost and security. However, traditional risk assessment methods in the defense industry often rely on approaches that may overlook or inadequately address uncertainties. There is a growing need for more comprehensive and adaptive risk analysis approaches that can take these uncertainties into account. Fuzzy logic-based multi-criteria decision-making (MCDM) methods offer an effective way to overcome these challenges. By considering the interdependencies between various risk factors and decision criteria, fuzzy logic-based MCDM methods offer a more holistic approach to risk analysis in the defense industry. These methods enable decision-makers to systematically evaluate and prioritize risks based on multiple criteria.

The Fine-Kinney Method, one of the risk analysis methods, provides a framework for risk assessment, facilitating the identification and prioritization of risks. This method

is also a widely used and accepted risk assessment method in the defense industry. However, traditional risk assessment is often based on specific data and certain information, failing to adequately address uncertainties. Integrating this method with fuzzy logic-based MCDM methods can create a more robust and reliable risk analysis tool by leveraging the strengths of both approaches. Therefore, the use of techniques such as fuzzy logic and Multi-Criteria Decision Making (MCDM) methods can improve risk management processes and provide a more solid foundation for decision-makers in the defense industry. Thanks to this integrated approach, risks in the defense industry can be evaluated more comprehensively, while decision-making processes can be made more efficient and resources can be used more effectively.

The subjectivity in experts' perspectives when performing risk analysis may affect the risk analysis and its results. In this context, a fuzzy approach using linguistic terms has been proposed to reduce the uncertainties and differences in expert opinions in determining the measures to be taken. For this reason, fuzzy logic-based MCDM methods were preferred in the evaluation of potential hazards. Giving the relative importance of criteria by using fuzzy numbers instead of exact numbers is one of the advantages of fuzzy MCDM methods [1]. Furthermore, fuzzy MCDM methods enable the consideration of multiple criteria and can reduce the complexity of the decision-making process.

The objective of this study is to introduce a new approach to conventional risk assessment by integrating fuzzy logic-based multi-criteria decision-making (MCDM) methods and risk analysis methods in the defense industry. Owing to this integration, hazards and risks were better understood, aiming for more effective measures to be taken. It has also been observed that comprehensive approaches that take into account uncertainties and subjective assessments have not been sufficiently addressed in the defense industry and that methodological studies on risk analysis and management are limited. This thesis study was aimed to provide an original contribution to address this deficiency and fill the gap.

Initially, a risk analysis was carried out using the Fine-Kinney method, which is one of the risk analysis methods, in a company operating in the defense industry and hazards were identified. The Fuzzy AHP method was used to weight the risk

parameters used in the Fine-Kinney method. These parameters are Probability, Frequency, and Consequence. Then, hazards were prioritized with the Fuzzy-VIKOR method using the obtained factor weights. In conclusion, the proposed two-stage fuzzy multi-criteria approach was enabled a more accurate and comprehensive assessment of occupational health and safety risks in the defense industry sector, thereby assisting in identifying more effective control measures for the hazards.

This thesis consists of six sections including the introduction and conclusion. In the first section of the study, a general introduction to the subject is given and the purpose of the thesis is mentioned. In the second section, studies on risk analysis and fuzzy multi-criteria decision-making methods are examined and a comprehensive literature review is made. In the third section, information is given about risk assessment and methodologies. Risk analysis methods are mentioned and the most commonly applied methods are briefly explained. In addition, the importance of risk analysis applications in the defense industry is emphasized. In the fourth section, the methods to be used in the study are explained in order. In this section, the methods are explained step by step, and the aim is to guide them so that they can be used in similar decision problems. First of all, the Fine-Kinney method, which is one of the risk analysis methods, is explained and information is given about its application. Then, the Fuzzy AHP and Fuzzy VIKOR methods, which are multi-criteria decision-making methods, are explained. The stages in the application process of the methods are shown step by step and their formulas are given. In the application section, which constitutes the fifth section of the study, the Fine-Kinney risk analysis method, the Fuzzy AHP method, and the Fuzzy VIKOR method are applied and the hazards are prioritized. In addition, sensitivity analysis was performed and the change in the ranking of the alternatives according to different  $v$  values used in the F-VIKOR method was examined. In the sixth and last chapter of the study, conclusion and discussion are included.

# CHAPTER 2

## LITERATURE REVIEW

Risk assessment has become very important in almost all sectors. Especially when it is a risky sector with high activities, great attention is paid to the risk assessment process. Therefore, many studies have been conducted with different risk assessment approaches [1].

Abdelgawad, M. and Fayek, A. R. (2010) executed a risk analysis by applying combined fuzzy failure mode and effect analysis (FMEA) and fuzzy analytical hierarchy process (AHP) methods in the construction industry [2]. They purposed to extend the application of FMEA to risk management in the construction industry in their study. They used fuzzy logic and fuzzy AHP to address the limitations of traditional FMEA with the proposed approach and applied a case study to validate. With the obtained results, they revealed that combined fuzzy FMEA and fuzzy AHP can eliminate various disadvantages of traditional FMEA applications.

Mızrak Özfirat, P. (2014) integrated fuzzy logic with Failure Modes and Effects Analysis (FMEA), one of the modern risk analysis methods, and applied it in the mining sector, one of the riskiest sectors [3]. She addressed the three criteria defined in FMEA, namely probability, severity, and detection, with the fuzzy prioritization method, which is one of the fuzzy analytic hierarchy process (FAHP) techniques in her methodology. Identification of risks and creation of pairwise comparison matrices were made by taking the opinions of eight mining engineers who are experts on the subject. She aimed to obtain more realistic results by applying fuzzy logic rules and to demonstrate the usability of the developed method by applying it in the high-risk underground mining sector.

Gül, M. and Güneri, A.F. (2016) used fuzzy multi-criteria decision-making methods to evaluate potential hazards in the aluminum industry [1]. They presented a combined fuzzy AHP-fuzzy TOPSIS risk assessment methodology based on the decision matrix risk assessment (DMRA) technique and applied them to an aluminum industrial

facility located in Tekirdağ, Turkey. In the first stage, the severity and likelihood levels of risks were measured using DMRA, a quantitative risk assessment technique. Subsequently, they weighted the likelihood and severity parameters of the hazards using fuzzy AHP. In the final stage, the fuzzy TOPSIS method was employed to determine the priority rankings of 23 different hazard groups. Linguistic variables were used to evaluate these two factors to reduce the inconsistency in decision-making with the proposed fuzzy approach. In this way, they aimed to reveal important hazards and suggest control measures to manage them.

Gül, M. et al. (2017) carried out a case study using a two-stage fuzzy multi-criteria approach in occupational health and safety risk assessment of a hospital. Unlike classical risk assessment methods, they considered five parameters [4]. These parameters were severity, occurrence, undetectability, sensitivity to maintenance non-execution, and sensitivity to personal protective equipment (PPE) non-utilization. First, they used Buckley's Fuzzy AHP to weight these five risk parameters, taking into account pairwise comparison and fuzzy linguistic ratings. In the second stage, the risk prioritization of hazards was determined using the Fuzzy VIKOR method based on these weighted parameters. Fuzzy VIKOR is a method that aims to identify the best solution by evaluating alternatives relative to each other. This approach allowed for prioritizing hazards in different departments of the hospital and proposing appropriate control measures for each hazard.

İlbahar, E. et al. (2018) evaluated the risks and hazards of the excavation process at a construction yard based on expert opinions in their study [5]. They calculated risk values in terms of occupational health and safety using an integrated method. Unlike the literature, they used the Pythagorean fuzzy AHP method to make risk assessment techniques work more effectively. Their proposed approach consists of a combination of Pythagorean fuzzy proportional risk assessment (PFPRO), Fine Kinney, Pythagorean fuzzy analytic hierarchy process, and a fuzzy inference system. They concluded that the proposed integrated method provides reliable and consistent results that contain more information about the uncertainty of decision-makers.

Can, G. F., and Toktaş, P. (2018) used fuzzy logic combined with multi-criteria decision-making in the warehouse acceptance process of a tractor manufacturing

company [6]. In this regard, they proposed a three-stage fuzzy risk matrix-based MCDM approach for risk assessment in their study. In the first stage, they used the fuzzy decision-making trial and evaluation laboratory (F-DEMATEL) method, which is one of the MCDM methods, to determine the importance weights of the risk factors. DEMATEL can present the cause-effect relations between the risk factors by dividing them into cause-and-effect groups [7]. In the second stage, fuzzy risk degrees of risk types were calculated considering the importance weights of risk factors. For this aim, fuzzy risk matrix is used. In the third stage, they determined corrective-preventive measures for each type of risk. They then ranked them according to weighted fuzzy values using multi-attributive border approximation area comparison (F-MABAC). Finally, they presented the application of the proposed risk assessment approach in a warehouse.

Gül, M., and Çelik, E. (2018) studied the fuzzy-based Fine-Kinney risk assessment approach for rail transportation systems and compared it with the classical Fine-Kinney method [8]. In the proposed approach, linguistic terms rather than exact numbers were used to evaluate the parameters of probability (P), exposure (E), and consequence (C) of Fine Kinney. They aimed to provide a perspective on improving safety in the public transportation industry with their case study and also emphasized the importance of such an assessment in the rail transportation area.

Çalık, A. (2018) aimed to provide an integrated fuzzy AHP and TOPSIS approach for prioritizing and analyzing risks in supply chain management and implemented for a company in the automotive spare part industry in his work [9]. First, the priorities of the criteria considered in the risk assessment method were determined by the fuzzy AHP method by creating pairwise comparison matrices. Subsequently, risk assessments of the suppliers were obtained using verbal variables. Risk scores of suppliers were calculated with the TOPSIS method by using the determined risk level weights and risk assessments. Finally, the rankings of the suppliers according to their risk levels were obtained.

Fattahi, R., and Khalilzadeh, M. (2018) performed risk assessment under a fuzzy environment using a hybrid method based on fuzzy FMEA, extended fuzzy MULTIMOORA, and fuzzy AHP methods [10]. They implemented it in a Steel

Industries Factory to demonstrate the applicability and benefits of their proposed fuzzy hybrid method. The weights of the three risk factors and the weights of each failure mode were considered at the same time in the proposed method. They calculated the weight of each failure mode with the proposed fuzzy MULTIMOORA method based on three criteria: time, cost, and profit. They aimed to allow for more precise computation of risk priority numbers (RPN) as well as increased efficiency of the FMEA method with their study.

Gül, M. and Ak, M. F. (2020) conducted a study on the evaluation of occupational risks from human health and environmental perspectives [11]. They carried out a case study on risk assessment in a marble factory to demonstrate the applicability of the approach. In their study, they combined two multi-criteria decision-making methods called the best and worst method (BWM) and multi-attribute ideal real comparative analysis (MAIRCA) in a fuzzy environment. They used Fuzzy BWM to calculate the relative importance of three risk factors named “probability, frequency, and severity” of the Fine Kinney method. Afterward, they applied fuzzy MAIRCA to rank hazards according to their risk level using importance values obtained by Fuzzy BWM. With this improved approach, they aimed for occupational health and safety experts and other relevant decision-makers to conduct a more robust risk analysis of their factories.

Hacıbektaşoğlu, S.E. et al. (2022) conducted risk analysis by applying the fuzzy logic-based hybrid fuzzy SWARA & fuzzy VIKOR methods in a company in the chemical industry [12]. They used the probability, exposure, and severity criteria of the Fine-Kinney method as criteria and evaluated 18 hazards. First of all, these criteria used in risk analysis were weighted with the f-SWARA method. After the criteria weighting, the hazards were analyzed using the f-VIKOR method, and the priority order was determined. At the end of the study, they compared the results of the analysis made with the traditional Fine-Kinney method and the results of the analysis of the hybrid fuzzy SWARA & fuzzy VIKOR method proposed within the scope of the study. They aimed to improve a more useful and sensitive hybrid risk analysis method in their study.

Bayhun, S. et al. (2023) made a hybrid application using Fuzzy Decision-Making Trial and Evaluation Laboratory (DEMATEL) and Fuzzy Combinable Distance Based

Assessment (CODAS) methods for the risk assessment process in a factory operating in the food production sector [13]. Firstly, they calculated the factor weights of the criteria with the fuzzy DEMATEL method. They prioritized occupational hazards and risks arising from hazards with the fuzzy CODAS method using the weights obtained in the second step. In their research, they aimed to identify the sources of occupational accidents that may occur in the food industry and thus provide an effective way to increase business performance based on corrective and preventive actions.

Another application in the mining sector is the work of Mutlu, M. et al. (2024). They proposed a new risk assessment approach using hybrid MCDM models and fuzzy sets for open-cast coal mine [14]. They evaluated to determine risk scores based on non-fatal occupational accidents and conducted a case study. In their study, they used Pythagorean fuzzy AHP to obtain risk scores of the criteria and the sub-criteria. Then, they used the fuzzy TOPSIS and Paksoy approach based on interval type-2 fuzzy sets (IT2FSs) approach for risk-based ranking.

Ak, M. F., & Demir, E. (2024) also made a case study on rail transportation systems [15]. They combined the modified Fine-Kinney approach with the interval-valued spherical fuzzy (IVSF) extension of the TOPSIS method. In addition to the severity, probability, and discovery parameters already present in the Fine-Kinney method, they also considered the cost, preventability, and personal protective equipment (PPE) parameters. In their study, unlike traditional methods, they aimed to make a more comprehensive risk assessment by integrating IVSF clusters to improve the handling of uncertainty.

Satici, S.R. and Mete, S. (2024) developed a Pythagorean fuzzy-based risk model to appraise risks in lifting equipment used in the energy distribution and investment sector [16]. In this context, they proposed an integrated approach to the Fine-Kinney-based Pythagorean Fuzzy Analytic Hierarchy Process (PFAHP) and Pythagorean fuzzy Complex Proportional Assessment (PFCOPRAS) methods for evaluating risks. They assessed the risk by considering the parameters of the classical Fine-Kinney method (probability, exposure, and consequence) and 25 hazards in their study. They used the PFAHP to weight the criteria in the first phase. Subsequently, they ranked the

25 hazards of lifting equipment operations using the PFCOPRAS method. They also conducted sensitivity analysis to validate the new method for risk assessment.

Korkusuz Polat, T., and Saltan Yaşlı, G. (2024) addressed the risks of a company producing energy storage systems and starting a new project in their study [17]. They used the classical Decision Matrix Risk Assessment (DMRA) method, which is one of the risk assessment methods, to evaluate the risks they identified. However, they divided the "severity" component of the classical DMRA method into three sub-components to be evaluated more specifically. These components are formed as the severity of delivery time, the severity of cost, and the severity of quality. Then, they applied the Fuzzy SWARA method in weighting the components. Lastly, they used the weights obtained from the Fuzzy SWARA method in the Fuzzy MOORA method and prioritized the risks. Thus, they aimed to increase the effectiveness of the classical risk assessment approach by detailing the "severity" component of the risk assessment components and using multi-criteria decision-making (MCDM) techniques.

Ayvaz, B. et al (2024) developed a risk assessment model for occupational hazards in the aquaculture sector [18]. In their study, they proposed an occupational risk assessment framework that integrates the Fine-Kinney method with the analytical hierarchy process (AHP) and weighted aggregated sum product assessment (WASPAS) under the Fermatean fuzzy set (FFS) environment. They used the AHP approach to calculate the weightage of the Fine-Kinney risk parameters (probability, exposure, and consequence) and they used the WASPAS method to find the ranking of the hazards. In the proposed model, they used the Fermatean fuzzy weighted geometric operator for the aggregation of expert opinions.

As can be seen from the literature review mentioned above, there are different studies on the application of risk analysis. However, it was understood that there are not many studies on risk assessment models related to fuzzy MCDM methods in the defense industry in the literature research conducted.

# CHAPTER 3

## RISK ASSESSMENT

### 3.1. Definition and Importance of Risk Assessment

According to the Regulation on Occupational Health and Safety Risk Assessment; risk assessment expresses the necessary studies conducted to identify the hazards present in the workplace or those that may come from outside, the potential harm they may cause to employees, the workplace, and the environment, and the measures to be taken against these hazards [19]. In this context, risk assessment is a critical process to ensure a safe working environment and protect the health and safety of employees.

Risk assessment is a systematic method that utilizes available data to estimate the frequency and potential consequences of specific events [1]. This approach helps organizations understand and manage risks by evaluating the likelihood of incidents and the severity of their impacts. Proactively identifying and addressing risks helps in creating a safer work environment, reducing the likelihood of accidents and injuries.

The purpose of risk assessment is to identify potential hazards and related risks that may occur during company activities. Thence, it allows the systematic definition of methods and principles for controlling expected or possible risks.

According to the regulation, risk assessment includes the following stages, including the design and establishment phases of workplaces [19]:

**1- Identification of Hazards:** This stage involves identifying all existing or potential hazards in the workplace. These hazards can range from chemical substances and physical dangers to biological risks and ergonomic issues. The goal is to identify all potential hazards comprehensively.

**2- Identification and Analysis of Risks:** Each of the identified hazards is taken into consideration separately, and the risks that may arise from them and their probability of occurrence are evaluated. It is determined who, what, in what way, and to what

extent may be harmed by these risks. This analysis involves determining risk levels based on the severity and likelihood of hazards.

**3- Risk Control Steps:** This involves planning and implementing measures to reduce or eliminate the identified risks. Control steps may include engineering controls, administrative controls, and the use of personal protective equipment, among other strategies.

**4- Documentation:** This stage involves recording the risk assessment activities and the measures taken in written form. It ensures that all evaluations, decisions, and actions are documented in detail.

**5- Renewal of Risk Assessment:** Risk assessments are reviewed and updated periodically or whenever there are significant changes in the workplace. This stage aims for continuous improvement and ensuring that the risk assessments remain current.

These stages represent a systematic and comprehensive approach to creating and maintaining a safe and healthy working environment. Therefore, it is of great importance to choose the right analysis and methodologies when performing risk assessment [20].

### **3.2. Risk Analysis and Methodologies**

Risk analysis is the process of identifying, assessing, and managing potential hazards in a system, project, or establishment. It assists decision-makers in understanding, measuring, and minimizing adverse outcomes by taking appropriate measures. Risk analysis is quite an important tool for the success, security, and sustainability of companies.

Risk analysis is the whole of the studies carried out that help organizations identify potential hazards they may encounter and implement measures to eliminate or minimize them. It involves several key steps, including identifying risks, assessing their likelihood and potential impact, and determining appropriate mitigation

strategies. Conducting risk analysis in every business is a necessity in terms of occupational health and safety [21].

Risk analysis methodologies systematically assess risks with structured approaches. These methodologies assist in determining the methods used during the risk assessment process. The risk analysis methodologies are divided into Qualitative and Quantitative.

Both quantitative and qualitative risk analyses are crucial in different contexts. Each has its techniques and tools, and they are often used to provide a comprehensive view of potential risks. Quantitative methods are valuable for their precision and ability to numerically model complex scenarios, while qualitative methods are beneficial for their flexibility and applicability when numerical data is unavailable.

### **3.2.1. Qualitative Risk Analysis**

Qualitative risk analysis allows for the qualitative assessment of risks. This method is often conducted using expert opinions and experiences. Qualitative analysis evaluates the likelihood and impacts of risks in non-numeric terms (e.g., low, moderate, high).

This approach provides a quick and cost-effective assessment but may not provide sufficient detail for precise results. Qualitative analysis often employs techniques such as SWOT analysis, brainstorming, and the Delphi method.

### **3.2.2. Quantitative Risk Analysis**

Quantitative risk analysis involves assessing risks with numerical data and mathematical models. This method expresses the probabilities and impacts of risks in numerical terms and is typically conducted using statistical methods.

Quantitative analysis provides more precise and reliable results but can be time-consuming and costly in data collection and analysis. Techniques such as Monte Carlo simulation, decision trees, and probability distributions are used in quantitative analysis.

### 3.3. Risk Analysis Methods

Risk analysis methods are specific tools and techniques used in the risk assessment process. There are many risk analysis methodologies available under the scope of quantitative and qualitative risk analysis methods [22]. Below, commonly used some risk analysis methods are explained in short.

#### 3.3.1. Fine-Kinney

The Fine-Kinney method is a widely used approach for assessing and prioritizing risks. It guides occupational safety professionals and managers in identifying which hazards carry the highest risk levels and how to manage these risks most effectively. By systematically identifying and assessing workplace hazards, this method assists in planning preventive measures and thus contributes to creating a safer working environment.

In Fine-Kinney risk analysis, which is a quantitative risk analysis method, there are three parameters: Probability (P), Frequency (F), and Consequence (C) [23]. This method determines risk levels by evaluating three key risk parameters. The steps of the Fine-Kinney method are as follows:

- Probability (P): The likelihood of the hazard occurring.
- Frequency (F): The frequency of exposure to the hazard.
- Consequence (C): The severity of the consequences if the hazard occurs.

The risk score of the hazards is obtained by the mathematical multiplication of these three parameters as shown in equation (3.1).

$$R = P \times F \times C \quad (3.1)$$

The Fine-Kinney method was explained in more detail in Chapter 4.

#### 3.3.2. Failure Modes and Effects Analysis (FMEA)

FMEA is a risk assessment method for the identification of potential failure modes and their effects in order to increase the reliability and safety of complex systems [24]. It

is effective for identifying failure modes in advance and taking corrective measures. This method involves identifying, evaluating, and prioritizing failure modes.

FMEA is broadly used as a reliability tool to recognize likely failures before they happen intending to reduce their risks. Since this method is based on finding, prioritizing, and minimizing failures, it has been broadly utilized in numerous types of industrial areas [25].

The traditional FMEA method uses a Risk Priority Number (RPN) to evaluate the risk level of a component or process. The RPN index is determined by calculating the product of Severity (S), Occurrence (O), and Detection (D) indexes [26].

### **3.3.3. Hazard and Operability Study (HAZOP)**

The hazard and operability study (HAZOP) method is a systematic examination structured to identify and evaluate problems that may pose a risk to personnel or equipment and prevent efficient operation. The HAZOP technique was initially developed to analyze chemical process systems but has later been extended to other types of systems [27]. It is widely used in industries such as chemical, petrochemical, and pharmaceutical.

This method provides a review process to identify potential hazards and operability problems within a system. In addition, it evaluates deviations and potential consequences by analyzing the components and functions of a system.

The HAZOP method offers a detailed and systematic approach but can be time-consuming and costly. Furthermore, the HAZOP study is typically conducted by a team of experts with a detailed knowledge of the system to be analyzed.

### **3.3.4. Fault Tree Analysis (FTA)**

The FTA (Fault Tree Analysis) method is one of the widely used modeling methods for risk analysis. This method is a risk assessment method that analyzes possible causes of failures and their combinations within a system. It is widely used in safety and reliability analyses.

FTA is a systematic way to obtain the reliability of complex systems both qualitatively and quantitatively by using exact values of root causes' occurrence probability [28]. It aims to determine the fundamental causes and potential consequences of failures.

This method is a top-down and deductive method, it examines systematically the reasons underlying the events [29]. The FTA method represents causes and combinations hierarchically in a tree structure. Schematics of a fault tree start with the "top event". The occurrence of the reasons is divided into the branches step by step. The analysis goes on at each level until the basic reasons or analysis lower limits are reached [28].

### **3.3.5. Event Tree Analysis (ETA)**

The Event Tree Analysis (ETA) is a method used to analyze the root causes of an event in a system and the potential consequences of these causes. It also shows the sequences of events related to the success or failure of management [30]. This method is employed to examine how events in complex systems can unfold and what chain reactions they might trigger. By examining the causes and consequences of events in detail, ETA contributes to the development of safety measures and risk management strategies. This method is particularly applied in fields such as industrial safety, risk management, and accident prevention.

The analysis starts with the initiating event that occurs in the system and is to be examined. This event is usually a failure, error, or accident. ETA systematically analyzes all possible outcomes that may follow an initiating event and how these outcomes can influence each other.

The analysis is visualized in the form of an event tree, with each branch representing a possible outcome of the initiating event. An event tree includes an initiating event, the likely subsequent events, and the final outcomes caused by the sequence of events [31]. This approach clearly outlines the possible development paths and results of events, identifying potential risks and the measures that can be taken to manage these risks.

### **3.3.6. Monte Carlo Simulation**

The Monte Carlo Simulation is used to model uncertainties and variability in risk analysis. This method uses random numbers and probability distributions to predict potential outcomes. It enhances the understanding of uncertainties and risks in complex systems. It is widely used in finance, engineering, and project management. The Monte Carlo Simulation is a powerful tool for evaluating cost, time, and performance risks in defense projects [32].

### **3.3.7. L Type Matrix analysis**

The L-type matrix method is an easy-to-implement method preferred in cause-effect analysis [33]. This matrix is a tool used in risk analysis and management, particularly for assessing and prioritizing risks. The L-shaped matrix is an efficient tool in the risk management process because it visually classifies and prioritizes risks. It provides decision-makers with a clear roadmap for developing risk management strategies based on identified priorities.

This matrix is typically presented in a 5x5 matrix format, where each cell is filled with values representing the probability and severity of a risk. These values are usually scaled from 1 to 5.

- Probability (P): It denotes the likelihood of a risk occurring. A value of 1 indicates low probability, while 5 signifies high probability.
- Severity (S): It represents the potential consequences if the risk materializes. A value of 1 denotes low impact, while 5 indicates high impact.

The matrix calculates a risk score for each risk to prioritize them effectively. The risk score is determined by multiplying the probability and severity values. It is decided whether the risk will be acceptable or not depending on the size of the risk score [34].

### **3.3.8. X Type Matrix Analysis**

The X-type matrix is a widely used tool in risk management processes, enabling a structured assessment of risks. This structured approach offers guidance to decision-makers on which risks to focus on, thereby enhancing the effectiveness of risk

management processes. This matrix is utilized in the processes of identifying, assessing, and prioritizing risks. The primary purpose of the X-type matrix is to systematically determine and evaluate potential risks and their consequences.

To carry out work in the X-type matrix, disciplined teamwork is required led by an experienced team leader. A five-year accident investigation must be conducted on the subject in the work area where this method will be applied [35].

One axis of the matrix represents the probability of the risks occurring, while the other axis represents the impact (severity) of these risks if they materialize. Each risk is positioned on the matrix based on these two parameters, allowing for a comprehensive assessment of the risk. The X-type matrix is typically visualized using color codes (e.g., red, yellow, green), making it easy to identify which risks need to be addressed more urgently and critically. The systematic structure of this matrix makes it an effective tool in risk management, helping decision-makers manage risks more efficiently.

### **3.3.9. Preliminary Hazard Analysis (PHA)**

Preliminary Hazard Analysis (PHA) is a qualitative risk analysis method used to identify and assess potential hazards during the early stages of a project or system. PHA is typically applied during the design, production, or development phase and systematically identifies hazards, possible causes, and consequences. Thus, since the hazard analysis is conducted during the development of a system, critical parts of the system can be improved [36]. This analysis method employs qualitative approaches such as brainstorming and expert judgment to identify hazards.

During the PHA process, the likelihood and impact of each hazard are assessed, allowing for the determination of risk levels and the development of preventive or mitigative measures. PHA is a critical tool in complex and high-risk projects to enhance safety and detect potential issues early on, thereby preventing costly and dangerous outcomes.

### **3.3.10. Cause and Effect Analysis**

Cause and Effect Analysis is a method used to identify and understand the root causes of a problem or event. This method is typically applied using a tool called a "Fishbone Diagram," which visually represents cause-and-effect relationships.

The diagram starts with a central line representing a central problem or result. It branches out to represent different factors or causes contributing to the occurrence of this problem. These branches generally represent factors such as people, methods, materials, machines, and the environment. A detailed analysis is made of the factors specified in each branch. In this way, it becomes possible to understand the root causes of the problem and develop appropriate solutions to eliminate or reduce these causes. This analysis method is widely used, especially for identifying the origins of complex or recurrent problems.

### **3.3.11. What if?**

The "What if?" method is a risk analysis technique commonly used in risk management processes. This method aims to identify potential risk scenarios and evaluate the likelihood of these scenarios occurring and their potential impacts. It can be applied at any stage of a transaction and can be carried out by less experienced risk analysts.

Essentially, it involves asking hypothetical questions to understand what could happen if a specific risk materializes. The answers to these questions help in understanding the consequences of the risk and assist in formulating risk management plans. This method supports a proactive approach and enables organizations to be prepared for possible risks they may encounter.

### **3.3.12. Checklist**

In this method, a pre-prepared checklist is used to identify possible risks at different stages of a specific process, system, or project. This checklist consists of items created by experts that represent potential hazards, safety standards to be adhered to, and critical points that need attention. Each item represents a specific risk area or hazard, and these items are reviewed systematically.

It can be effectively used in projects that are not complex and are conducted within certain standards. Due to its easily understandable and applicable nature, the Checklist Method is preferred by a wide range of users. Additionally, this method is easy to document, and the data obtained can be used as a reference for future risk assessments. However, the effectiveness of the Checklist Method depends on the comprehensiveness and accuracy of the prepared checklist. An incomplete or insufficiently prepared list may result in some risks being overlooked. Therefore, it is crucial to consult experts during the preparation of the checklist and to update the list regularly.

### **3.4. Applications of Risk Analysis in the Defense Industry**

The defense industry is a sector that includes high-risk and complex projects. Due to the nature of Defense Industry activities, they are more sensitive to risks due to factors such as focus on high technology, confidentiality, and sensitive products. Therefore, risk analysis is essential for identifying and managing uncertainties and potential hazards.

Risk analysis plays a critical role in ensuring the success and safety of projects in this sector. In the defense industry, risk analysis is widely used in planning, designing, developing, and operating projects. If risks are not managed well, sensitivities in the defense industry sector can potentially turn into crises in a short time. For this reason, risk management and risk analysis are processes that need to be addressed specifically for defense industry companies.

Risk analysis in the defense industry is critical for addressing and mitigating this sector's unique challenges and uncertainties. Therefore, given the high stakes and sensitivity of the defense industry, effective risk analysis is indispensable. The risk analysis helps defense companies navigate the complexities of technology development, project management, operational security, and strategic planning, ensuring that risks are identified, assessed, and mitigated before they can escalate into crises.

# CHAPTER 4

## METHODOLOGY

### 4.1. Fine-Kinney Method

The Fine-Kinney method is a systematic and quantitative analysis method used in occupational safety and risk management. This method was developed in 1976 as a risk assessment tool to control hazards [37]. It is particularly widely used in the processes of identifying hazards, assessing risks, and taking appropriate measures to prevent workplace accidents and dangerous situations.

The fundamental principle of the Fine-Kinney method is to calculate a risk score by evaluating three main components of risk. These components are:

- *Probability (P)*: This refers to the likelihood of a hazard occurring. Probability evaluates how often a hazard is likely to occur within a specified time frame.
- *Frequency (F)*: This refers to the frequency of exposure to the hazard. It indicates how often workers or equipment are exposed to the hazard.
- *Consequence (C)*: This refers to the severity of harm that would result if a hazard occurs. This harm is usually assessed based on factors such as the severity of injuries, equipment damage, or production loss.

In the Fine-Kinney method, the risk score (R) is calculated by multiplying these three components [38].

This formula allows for a quantitative expression of risk and helps in identifying high-risk situations. The calculated risk score is usually compared to a specific threshold value to determine whether the risk is acceptable. Preventive or corrective measures should be taken for risks that exceed the threshold value.

The ratings of the three parameters used in the Fine Kinney method are given in Tables 4.1, 4.2, and 4.3 Risk levels are given in Table 4.4.

**Table 4.1** Ratings of probability [38]

<b>Probability</b>	<b>Value</b>
Might well be expected	10
Quite possible	6
Unusual but possible	3
Only remotely possible	1
Conceivable but very unlikely	0.5
Practically impossible	0.2
Virtually impossible	0.1

**Table 4.2** Ratings of frequency [38]

<b>Frequency</b>	<b>Value</b>
Continuous	10
Frequent (daily)	6
Occasional (weekly)	3
Unusual (monthly)	2
Rare (a few per year)	1
Very rare (yearly)	0.5

**Table 4.3** Ratings of consequence [38]

<b>Consequence</b>	<b>Value</b>
Catastrophic (many fatalities)	100
Disaster (few fatalities)	40
Very serious (fatality)	15
Serious (serious injury)	7
Important (disability)	3
Noticeable (minor first aid accident)	1

Table 4.4 Risk levels [38]

Risk levels	Risk Situation
>400	Very high risk; consider discontinuing operation
200-400	High risk; immediate correction required
70-200	Substantial risk; correction needed
20-70	Possible risk; attention indicated
<20	Risk; perhaps acceptable

- **0-20: Risk:** At this level, the risk is considered negligible and usually no additional measures are required. Existing control measures are deemed sufficient.
- **21-70: Possible Risk:** At this level, the risk is considered low. The risk should be monitored, and existing controls should be reviewed, but no immediate action is necessary.
- **71-200: Substantial Risk:** At this level, the risk is moderate, and improvement measures should be taken. Enhancements to existing controls or additional measures may be necessary.
- **201-400: High Risk:** At this level, the risk is high and urgent measures need to be taken. Immediate action is required to minimize the hazards.
- **401 and Above: Very High Risk:** At this level, the risk is unacceptably high, and activities should be halted with comprehensive measures put in place. Such risks must be addressed immediately, and the hazard source must be completely eliminated.

These criteria guide the determination of acceptable risk levels and help decide which risks are acceptable or unacceptable. Additionally, when evaluating the acceptability of risks, the specific conditions of the workplace and the potential impacts on employee safety are taken into account. This assessment is a critical step for effectively managing risks and ensuring that employees have a safe working environment. In cases where the risk is deemed unacceptable, the identified control measures must be promptly implemented and monitored.

The application process of the Fine Kinney method is briefly shown in Figure 4.1.

### 1. Identification of Hazards

- All existing hazards in the workplace or the area to be analyzed are identified.

### 2. Evaluation of Risk Components

- For each hazard, the probability, frequency, and consequence factors are evaluated and scored separately.

### 3. Calculation of Risk Score

- The risk score for each hazard is calculated by multiplying the probability, frequency, and consequence scores.

### 4. Classification of Risks

- Hazards are classified and prioritized based on the obtained risk scores.

### 5. Determination of Measures

- Immediate intervention and control measures are identified and implemented for high and very high-risk hazards.

### 6. Monitoring and Review

- The effectiveness of the implemented measures is monitored and reviewed as necessary.

**Figure 4.1** Implementation process of the Fine-Kinney Method

Fine Kinney is a user-friendly and easy-to-understand method. It has a wide range of applications across different sectors. This method allows for the identification and assessment of hazards and risks without the need for complex mathematical models. Additionally, it is beneficial for visualizing and prioritizing risks. This enables businesses to make more effective and efficient decisions in their risk management processes.

The Fine Kinney method is an ideal approach for quick and effective risk assessment, especially for small and medium-sized enterprises. However, for more comprehensive and detailed risk analyses, it is recommended to use this method in conjunction with other methodologies.

## 4.2. Fuzzy AHP Method

The Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty in 1977, is one of the multi-criteria decision-making (MCDM) methods used in complex decision-making processes [39]. This method aims to determine the best option by comparing criteria and alternatives within a hierarchical structure when the decision maker has multiple criteria [40]. The AHP method allows decision-makers to evaluate various alternatives based on a set of criteria and sub-criteria. In addition, the problem is revealed and deconstructed in depth during the development of the hierarchical structure, which is a significant advantage of this method [41].

The process involves pairwise comparisons to determine the relative importance of criteria and alternatives, and the quantification of these comparisons. However, the classical AHP method with exact numbers cannot reflect the uncertainties and subjectivities entirely involved in decision-making. Therefore, the AHP method is extended into a fuzzy environment to better reflect uncertainty.

Fuzzy AHP (Fuzzy Analytic Hierarchy Process), on the other hand, is a method that combines the hierarchical structure of the traditional AHP with fuzzy logic to solve complex multi-criteria decision-making (MCDM) problems. Fuzzy logic, introduced by Zadeh in 1965, is a method for modeling imprecise or incomplete information [42]. Fuzzy logic is effective in evaluating uncertainty and imprecise information. It allows for a more flexible and realistic modeling of subjective judgments in AHP.

In Fuzzy AHP, comparisons are made using fuzzy numbers, which better express the uncertain or imprecise judgments of decision-makers. The values obtained as a result of pairwise comparison of each criterion are expressed as triangular fuzzy numbers. For example, if one criterion is "slightly more important" than another, fuzzy numbers are used to express this uncertainty.

The linguistic terms and their corresponding fuzzy numbers are given in Table 4.5. The scale is characterized by nine linguistic values whose corresponding fuzzy membership functions are triangular [37].

**Table 4.5** Linguistic terms and corresponding fuzzy values [37]

<b>Linguistic Terms</b>	<b>Fuzzy Values</b>
Absolutely Strong (AS)	(2, 5/2, 3)
Very Strong (VS)	(3/2, 2, 5/2)
Fairly Strong (FS)	(1, 3/2, 2)
Slightly Strong (SS)	(1, 1, 3/2)
Equal (E)	(1, 1, 1)
Slightly Weak (SW)	(2/3, 1, 1)
Fairly Weak (FW)	(1/2, 2/3, 1)
Very Weak (VW)	(2/5, 1/2, 2/3)
Absolutely Weak (AW)	(1/3, 2/5, 1/2)

Fuzzy numbers allow for better management of uncertainties and inconsistencies in the decision-making process, leading to more realistic and reliable results. Fuzzy AHP offers a more flexible and sensitive approach, particularly for complex and uncertain decision-making problems, helping decision-makers achieve healthier and more consistent outcomes.

Fuzzy AHP addresses the limitations of classical AHP, enabling better management of subjective evaluations and minimizing information gaps. This method is widely used in various fields such as engineering, management, supply chain management, project management, healthcare, and more. This versatility and effectiveness make Fuzzy AHP a valuable tool in numerous complex decision-making scenarios.

The steps involved in the Fuzzy AHP process are summarized in Figure 4.2.

### 1. Establishing the Hierarchy

- The decision problem is structured into a hierarchy comprising the main goal, criteria, sub-criteria, and alternatives.

### 2. Constructing Pairwise Comparison Matrices

- Each pair of criteria and alternatives is compared using fuzzy numbers. These matrices incorporate the uncertainties and inconsistencies in decision-makers' evaluations.

### 3. Determining Fuzzy Numbers

- Fuzzy numbers are assigned to each comparison to reflect the subjective assessments and uncertainties of decision-makers.

### 4. Calculating Fuzzy Priorities

- Fuzzy priorities for the criteria and alternatives are computed from the pairwise comparison matrices using the assigned fuzzy numbers.

### 5. Deriving Fuzzy Weights

- Fuzzy weights for each criterion and alternative are determined based on the fuzzy priorities.

**Figure 4.2** The steps involved in the Fuzzy AHP process

There is more than one Fuzzy AHP method proposed in the fuzzy MCDM literature. Since some Fuzzy AHP methods have limitations, Buckley's (1985) method was used in the application of this study.

#### 4.2.1. Buckley's Fuzzy AHP

Buckley's Fuzzy AHP method is an enhanced version of the classical Analytic Hierarchy Process (AHP) with the integration of fuzzy logic, particularly useful in decision-making processes where uncertainty and ambiguity are high. Developed by James J. Buckley in 1985, this method replaces the exact (deterministic) values in classical AHP comparison matrices with fuzzy numbers, allowing decision-makers to more accurately express uncertain or imprecise evaluations. Buckley's Fuzzy AHP

method employs triangular fuzzy numbers (TFNs) and fuzzy comparison matrices to determine the relative importance of criteria and alternatives.

The stages of Buckley's Fuzzy AHP are given below.

- **Step 1: Pairwise comparison matrices**

Pairwise comparisons are constructed among all the criteria in the hierarchy system. Linguistic terms are used in determining the relative importance of each two criteria, based on equations (4.1) and (4.2).

$$\tilde{M} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots & \tilde{a}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & 1 \end{bmatrix} \quad (4.1)$$

$$\tilde{a}_{ij} = \begin{cases} \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9} & \text{criterion i is the relative importance to criterion j} \\ 1 & i = j \\ \tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1} & \text{criterion j is the relative importance to criterion i} \end{cases} \quad (4.2)$$

$\tilde{M}$  = Pairwise comparison matrix

$\tilde{a}_{ij}$  = Represents the comparison value of the i.criterion on the j.criterion as a fuzzy triangular number.

Here the “tilde (~)” sign indicates triangular numbers.

- **Step 2. Fuzzy geometric mean matrix**

The fuzzy geometric mean matrix is defined using the geometric mean technique by equation (4.3).

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \dots \otimes \tilde{a}_{in})^{1/n} \quad (4.3)$$

$\tilde{r}_i$  = Fuzzy geometric mean value.

- **Step 3. Fuzzy weights of each criterion**

For each criterion, the fuzzy weights are obtained by equation (4.4).

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \dots \oplus \tilde{r}_n)^{-1} \quad (4.4)$$

$\widetilde{w}_i$  = fuzzy weight of criterion i.

$$\widetilde{w}_i = lw_i, mw_i, uw_i$$

Here, “ $lw_i, mw_i, uw_i$ ” values show the lower, middle, and upper values of the fuzzy weight of criterion i [43].

- **Step 4. Non-fuzzy weight of parameters (Defuzzification)**

The center of area (COA) method is used to find the best non-fuzzy performance, as in equation (4.5).

$$w_i = [(uw_i - lw_i) + (mw_i - lw_i)] / 3 + lw_i \quad (4.5)$$

Lastly, the weights of the criteria were calculated by performing the normalization process given in equation (4.6).

$$w = \frac{w_i}{\sum_{i=1}^n w_i} \quad (4.6)$$

### 4.3. Fuzzy VIKOR Method

The VIKOR (Vise Kriterijumska Optimizacija I Kompromisno Resenje) method was developed by Opricovic in 1998 [43]. This method is one of the multi-criteria decision-making (MCDM) methods developed for multi-criteria optimization and compromise solutions of complex systems [44]. The VIKOR is designed to find the optimal solution by considering the trade-offs between different criteria. It is a helpful tool in multicriteria decision-making, particularly in a situation where the decision maker is not able or does not know to express his/her preference at the beginning of system design.

This method focuses on ranking and selecting from a set of alternatives. It determines compromise solutions that are the closest to the “ideal” for a problem with conflicting criteria, which helps the decision-makers to reach a final decision [45].

The VIKOR method identifies the best alternatives by measuring the proximity degree of the solution, using the concepts of Positive Ideal Solution (PIS) and Negative Ideal

Solution (NIS). The VIKOR seeks a compromise solution in the ranking of alternatives by balancing the greatest group utility and the smallest individual regret.

On the other hand, the fuzzy VIKOR method enhances the advantages of the classical VIKOR method by incorporating fuzzy logic. The fuzzy VIKOR method, unlike the classical VIKOR method, includes fuzzy evaluations of criteria and alternatives. Instead of using precise data as in the VIKOR method, it uses data containing uncertainty and vagueness. This makes the decision-making process more realistic and provides more reliable results, especially in complex and highly uncertain situations. The Fuzzy VIKOR method calculates the distances of alternatives from the fuzzy positive ideal solution (FPIS) and the fuzzy negative ideal solution (FNIS) based on fuzzy logic principles.

In the fuzzy VIKOR method, decision-makers rate alternatives or criteria using linguistic terms. These linguistic terms are numericalized according to their fuzzy number equivalents. The linguistic terms and their corresponding triangular fuzzy numbers used in the evaluation of rankings are given in Table 4.5.

Fuzzy logic models real-world uncertainties more effectively by using fuzzy numbers instead of precise numbers. It takes into account many quantitative and qualitative criteria together. In this way, quantitative values of linguistic variables that cannot be expressed precisely, such as very poor, poor, and fair, are found [46]. This enables decision-makers to make more flexible and realistic evaluations. Therefore, the Fuzzy VIKOR method is a powerful tool for multi-criteria decision-making processes involving uncertainty and complexity. It offers significant advantages to decision-makers in selecting the most suitable alternatives.

The steps involved in the Fuzzy VIKOR process are summarized in Figure 4.3.

### 1. Identification of Criteria and Alternatives

- The criteria of the decision-making problem and the alternatives to be evaluated according to these criteria are determined.

### 2. Definition of Fuzzy Criteria Weights and Performance Values

- The performance values of criteria and alternatives are expressed as fuzzy numbers. This is usually done using triangular fuzzy numbers.

### 3. Construction of Fuzzy Decision Matrix

- A fuzzy decision matrix is created containing the performance values of the alternatives under each criterion. In this matrix, each cell is represented by a fuzzy number.

### 4. Determination of Fuzzy Ideal and Anti-Ideal Solutions

- For each criterion, fuzzy ideal (best) and fuzzy anti-ideal (worst) performance values are determined.

### 5. Calculation of Fuzzy Discordance and Solution Values

- The distances of the alternatives to the fuzzy ideal and fuzzy anti-ideal solutions are computed. This calculation is done using fuzzy arithmetic operations. The distances of the alternatives to these values show how good each alternative is.

### 6. Creation of Fuzzy Compromise Ranking

- Alternatives are ranked according to the calculated fuzzy incompatibility values. This ranking helps in finding the most suitable solution.

**Figure 4.3** The steps involved in the Fuzzy VIKOR process

The application stages of the Fuzzy VIKOR method and the formulas used in the calculation of the method are given below.

- ***Step 1: Determine of criteria and alternatives***

The criteria of the decision-making problem and the alternatives to be evaluated according to these criteria are determined by the decision-making group. The number of alternatives is considered as  $m$  and the number of criteria is  $n$ .

- **Step 2: Creation of fuzzy decision matrix**

In this stage, the fuzzy decision matrix is created. A fuzzy decision matrix of size  $m \times n$  is created, with  $m$  alternatives in the rows and  $n$  criteria by which each alternative is evaluated in the columns.

While creating the matrix, the linguistic criteria given in Table 4.5 and the corresponding triangular fuzzy values are used. The fuzzy decision matrix is shown in (4.7).

$$\tilde{D} = \begin{bmatrix} \tilde{f}_{11} & \tilde{f}_{12} & \dots & \tilde{f}_{1j} \\ \tilde{f}_{21} & \tilde{f}_{22} & \dots & \tilde{f}_{2j} \\ \dots & \dots & \dots & \dots \\ \tilde{f}_{i1} & \tilde{f}_{i2} & \dots & \tilde{f}_{mn} \end{bmatrix} \quad (4.7)$$

$$i=1,2,\dots,m ; j=1,2,\dots,n$$

- **Step 3: Defuzzification**

Defuzzification of the elements of the fuzzy decision matrix for the criteria weights and the alternatives into crisp values is carried out. A fuzzy number ( $a$ ) can be converted into a crisp number by equation (4.8).

$$a = \frac{a_1 + 4a_2 + a_3}{6} \quad (4.8)$$

- **Step 4: Determination of fuzzy best and fuzzy worst values**

The fuzzy best ( $f_j^*$ ) and fuzzy worst ( $f_j^-$ ) values of all criteria ratings ( $j$ ) and alternatives ( $i$ ) are determined using equations (4.9) and (4.10).

$$f_j^* = \max_i \{f_{ij}\} \quad (4.9)$$

$$f_j^- = \min_i \{f_{ij}\} \quad (4.10)$$

- **Step 5: Calculation of  $S_i$  and  $R_i$  values**

$S_i$  and  $R_i$  values are calculated using equations (4.11) and (4.12).

$$S_i = \sum_{j=1}^n w_j \left( \frac{f_j^* - f_{ij}}{\tilde{f}_j^* - \tilde{f}_j^-} \right) \quad (4.11)$$

$$R_i = \max_j w_j \left( \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right) \quad (4.12)$$

$w_j$  = the weight of criteria.

$S_i$  = the sum of the distance of alternative  $i$  to the best fuzzy value according to all criteria.

$R_i$  = the maximum distance of alternative  $i$  to the worst fuzzy values according to  $j$  criteria.

- **Step 6: The calculation of  $S^*$ ,  $S^-$ ,  $R^*$ ,  $R^-$  values**

$S^*$ ,  $S^-$ ,  $R^*$ ,  $R^-$  values are calculated using equations (4.13) and (4.14).

$$S^* = \min_i S_i, \quad S^- = \max_i S_i \quad (4.13)$$

$$R^* = \min_i R_i, \quad R^- = \max_i R_i \quad (4.14)$$

$S^*$  = the maximum group utility.

$R^*$  = the minimum individual regret among those with different views.

- **Step 7: The calculation of  $Q_i$  value**

$Q_i$  value are calculated using equation (4.15).

$$Q_i = \frac{v(S_i - S^*)}{S^- - S^*} + (1 - v) \frac{R_i - R^*}{R^- - R^*} \quad (4.15)$$

$Q_i$  value is determined by evaluating  $S^*$ ,  $S^-$ ,  $R^*$ , and  $R^-$  values together. While the  $\nu$  value expresses the importance of the strategy that provides maximum group benefit,  $1-\nu$  represents the individual regret value. For the conciliatory majority,  $\nu = 0,5$  can be taken [47].

- **Step 8: Ranking the alternatives according to the  $S_i$ ,  $R_i$  and  $Q_i$  values**

The alternatives are ranked according to the  $S_i$ ,  $R_i$  and  $Q_i$  values obtained. The smallest of the  $Q_i$  values indicates the most dangerous situation, while the largest indicates the least dangerous situation.

In this context, the hazard priority ranking is determined by ranking the  $Q_i$  value from smallest to largest.

- **Step 9: Determining the compromise solution**

It is determined whether the best alternative is a compromise solution. To determine the compromise solution, it is checked whether the following two conditions are met [48].

**Condition 1:** Acceptable advantage

$$Q(A^{(2)}) - Q(A^{(1)}) \geq DQ \quad (4.16)$$

$$DQ = \frac{1}{m-1} \quad (m = \text{number of alternatives}) \quad (4.17)$$

Here, the value of  $A^{(1)}$  represents the first alternative with the lowest  $Q$  value, and the value of  $A^{(2)}$  represents the second alternative.

**Condition 2:** Acceptable stability in decision-making

Alternative  $A^{(1)}$  must also be the best alternative in the ranking made according to  $S$  and/or  $R$  values. This compromise solution is stability in the decision-making process.

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of [49]:

- If Condition 2 is not met; alternatives  $A^{(1)}$  and  $A^{(2)}$  are accepted as compromise solutions.
- If Condition 1 is not met; alternatives  $A^{(1)}, A^{(2)}, \dots, A^{(m)}$  are determined by the inequality shown in (4.18).

$$Q(A^{(m)}) - Q(A^{(1)}) < DQ \quad (4.18)$$



# CHAPTER 5

## IMPLEMENTATION

In this study, it was aimed to bring a new perspective to the traditional risk assessment approach with the integration of Fuzzy Logic and MCDM methods into risk analysis applications in the field of Occupational Health and Safety. In this context, a fuzzy approach using linguistic terms has been proposed to reduce the uncertainties and differences in expert opinions in determining the measures to be taken.

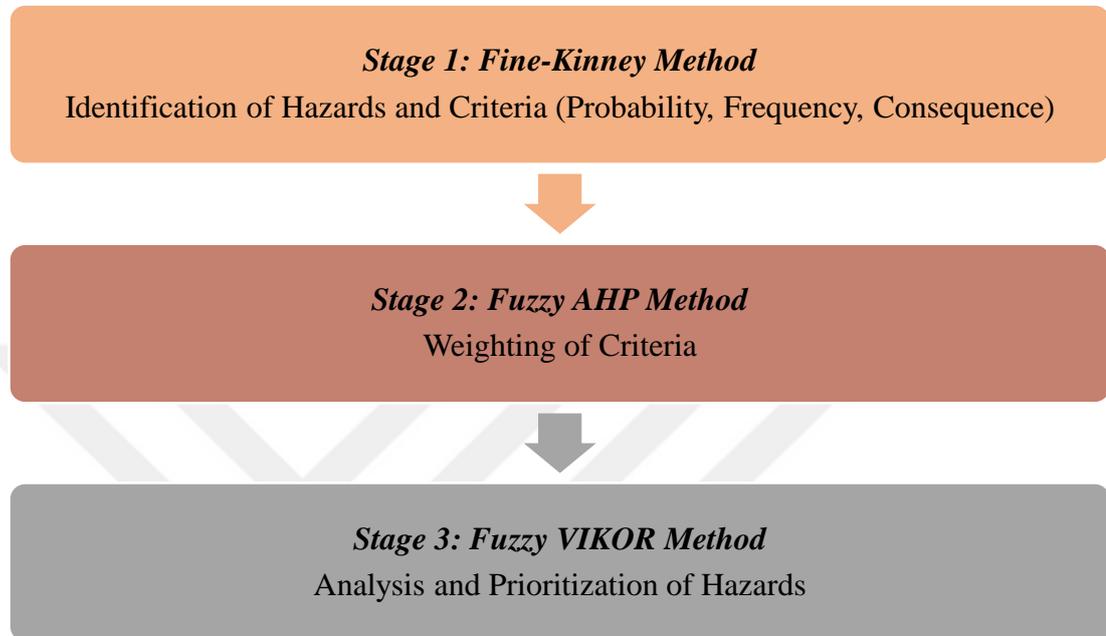
A risk analysis was carried out using the Fine-Kinney method in a company operating in the defense industry and hazards were identified. This method was used for identifying and evaluating hazards in the workplace by quantifying risk based on the probability of occurrence, severity of consequences, and exposure frequency. Subsequently, the Fine-Kinney method was enhanced by integrating with the Fuzzy AHP and the Fuzzy VIKOR procedures, both of which are multi-criteria decision-making (MCDM) approaches. With this integrated approach, it was aimed to understand uncertainties and risks better and ensure more realistic and effective decision-making.

In the first stage, sixty hazards were identified by taking expert opinions in the Fine Kinney risk analysis application. Then, the risk score of these identified sixty hazards was calculated by mathematical multiplication of the Probability (P), Frequency (F), and Consequence (C) parameters.

In the next phase, the values were obtained as a result of the pairwise comparison of each criterion (Probability, Frequency, and Consequence) were expressed as triangular fuzzy numbers, and the weights of the criteria were found by applying each step of the Fuzzy AHP respectively.

In the last stage, each step of the Fuzzy-VIKOR method was applied respectively by using the obtained criterion weights, and the hazards were prioritized.

In this implementation section, details about the approaches were given and the application of the methods were explained step by step. The flowchart of the proposed approach is shown in Figure 5.1.



**Figure 5.1** Flowchart of the proposed approach

### **5.1. Application of Fine-Kinney Method**

In a company operating in the defense industry, possible dangers were first identified by taking expert opinions. While determining the hazards, five experts experienced in the sector were consulted and the consensus was reflected. Then, the risk scores of these hazards were determined according to the Fine-Kinney risk analysis method.

While determining the hazards, the production area, types of equipment, stock and transportation processes, quality processes, work areas, and general hazards that may be encountered throughout the company were taken into account.

The risk assessment table showing the determined hazards and possible risks associated with hazards is presented in Table 5.1.

**Table 5.1** Determined hazards and risks

<i>HAZARD NO</i>	<i>SOURCE OF HAZARD</i>	<i>HAZARD</i>	<i>RISK</i>	<i>TYPE OF AFFECT</i>
H1	Pressurized Gases	Explosion of pressurized gas cylinders/bundles (Argon, Helium, Nitrogen, etc.)	Inhalation of pressurized gases by employees, Explosion of the tube	Poisoning, Injury, Death
H2	Electric	Failure to perform electrical installation, grounding, and lightning rod checks	Risk of electric shock	Serious injury, Death
H3	Work Equipment	Failure to measure the radiation level of employees using the devices	Radiation exposure during the use of devices	Health problems
H4	Emergency Situations	Lack of the sufficient number of fire extinguishers	Delay in intervention in case of a possible fire	Death
H5	Emergency Situations	Failure to perform periodic maintenance and checks of fire extinguishers	Delay in intervention in case of a possible fire	Death
H6	Consumable	Exposure of workers to harmful dust made of Aluminum and Titanium alloys during the use of devices	Lack of awareness about exposure to dust and volatile substances	Health problems, Occupational diseases
H7	Work Equipment	Lack of boiler room maintenance and control reports	Risk of accident due to use of unsafe work equipment	Injury, Serious injury, Death
H8	Work Equipment	Lack of body grounding of machines	Risk of accident due to use of unsafe work equipment	Serious injury, Death
H9	Emergency Situations	Fire extinguishers not suitable for possible fire	Doing the wrong intervention in case of possible fire	Death
H10	Work Equipment	The employee not using anti-static wristbands during machine use	Possibility of explosion due to static electricity generation	Injury, Serious injury
H11	Emergency Situations	Emergency exit doors are closed or the presence of obstacles on escape routes	Inability to evacuate or delay in evacuation in possible emergencies	Death
H12	Work Equipment	Lack of suitable magnetic fixing equipment on the surface grinding machine	Risk of the piece to be ground being thrown out of place	Injury, Serious injury
H13	Work Equipment	Employee waiting on the side where sawdust splashes during grinding	Splashes of sawdust on the face or eyes of the employee during grinding	Injury
H14	Work Equipment	Splashing of broken parts during processing of post-production parts	Splashes of fragments on the face, eyes, or body of the employee	Injury
H15	General	Lack of eye showers in areas where chemicals are used	Burrs getting into the eyes	Health problems
H16	Consumable	Lack of dust and volatile substance measurements	Lack of awareness about exposure to dust and volatile substances	Health problems
H17	Maintenance and Repair	Not using ear protection during noisy work	Exposure to noise	Health problems
H18	Work Equipment	Failure to use appropriate personal protective equipment during use and maintenance of the sandblasting machine	Exposure to harmful alloy dust	Health problems
H19	Work Equipment	Lifting loads above capacity with dust lifting and placing equipment	Work accident as a result of above capacity overload	Serious injury, Death
H20	Work Equipment	Not performing sandblasting machine filter replacement and periodic maintenance	Risk of accident due to use of unsafe work equipment	Serious injury, Death

**Table 5.1 (Continued)** Determined hazards and risks

<i>HAZARD NO</i>	<i>SOURCE OF HAZARD</i>	<i>HAZARD</i>	<i>RISK</i>	<i>TYPE OF AFFECT</i>
H21	Chemical Substances	Not labeling of chemical substance containers	Lack of awareness about chemical substances	Poisoning, Injury, Death
H22	Waste Areas	Failure to determine locations for collection and storage of hazardous and non-hazardous waste areas	Exposure due to improper waste collection	Health problems
H23	Work Equipment	Formation of oil mist as a result of using boron oil during the surface grinding process	Inhalation of chemical oil vapor in the environment, lack of ambient measurement	Injury, Serious injury
H24	Chemical Substances	Not using fire-resistant cabinets in areas where chemical powder alloys are stored	Exposure to fire and explosion	Serious injury, Death
H25	Pressurized Gases	Overturning of pressure vessels	Contact of pressurized gases with employees and equipment	Poisoning, Injury, Death
H26	Work Equipment	Lack of safe use instructions for power tools	Lack of awareness about power tools	Serious injury, Death
H27	Work Equipment	Failure to maintain and control dust removal and placement equipment	Risk of accident due to use of unsafe work equipment	Serious injury, Death
H28	Electric	Lack of insulating mats under electrical panels	Risk of electrocution in case of possible intervention	Electric shock, Injury, Death
H29	Personal Protective Equipment	Not providing necessary personal protective equipment to employees	Increased violence in case of a possible accident	Serious injury, Death
H30	Work Equipment	Lack of periodic maintenance and control of pressure vessels	Risk of accident due to use of unsafe work equipment	Serious injury, Death
H31	Electric	Not having a fire extinguisher in places with electrical hazards	Inability to intervene in case of possible fire	Serious injury, Death
H32	Chemical Substances	Not using Personal Protective Equipment while working with chemicals	Chemical exposure	Poisoning, Injury, Death
H33	Maintenance and Repair	Manual lifting and carrying of heavy loads	Risk of load falling, musculoskeletal disorders	Serious injury, Death
H34	Maintenance and Repair	Bringing limbs such as hands and arms closer to rotating parts during work	Limbs or clothing getting caught in rotating parts	Injury, Serious injury
H35	Work Equipment	Using power tools for purposes other than their intended purpose	Work accident and injury	Serious injury, Death
H36	Maintenance and Repair	Wearing inappropriate clothing during maintenance and repair activities	Risk of getting trapped in rotating equipment, Non-ergonomic work	Serious injury, Death
H37	Emergency Situations	Presence of obstacles in front of fire extinguishing equipment	Delay in intervention in case of a possible fire	Death
H38	Personal Protective Equipment	Not using appropriate personal protective equipment while using machines	Splashing of pieces into eyes	Injury, Serious injury
H39	Work Equipment	Lack of instructions for the safe use of hand tools	Lack of awareness about hand tools	Injury, Serious injury
H40	General	Work gloves not suitable for contact with chemicals	Chemical exposure	Burn, Injury

**Table 5.1 (Continued)** Determined hazards and risks

<i>HAZARD NO</i>	<i>SOURCE OF HAZARD</i>	<i>HAZARD</i>	<i>RISK</i>	<i>TYPE OF AFFECT</i>
H41	Maintenance and Repair	Touching hot surfaces with bare hands	Contact with hot surface	Burn, Injury, Serious injury
H42	General	The presence of objects or holes on the ground that may cause tripping and falling	Trip, fall, injury	Injury, Serious injury
H43	General	Presence of slippery or wet ground	Slip, fall, injury	Injury, Serious injury
H44	Chemical Substances	Use of chemicals for purposes other than their intended purpose	Burn, injury, poisoning, death	Poisoning, Injury, Death
H45	Chemical Substances	Damaged chemical containers	Occurrence of chemical substance leaks	Poisoning, Injury, Death
H46	Pressurized Gases	Presence of leakage at the connection points of pressurized gases	Inhalation of harmful gases by employees	Health problems
H47	General	Lack of ventilation	Health problems	Health problems
H48	Maintenance and Repair	Failure to use appropriate personal protective equipment and ventilation systems in works with dust or gas emissions	Exposure to dust and gas	Health problems
H49	Maintenance and Repair	Lack of instructions for maintenance and repair activities	Risk of accident due to lack of awareness	Serious injury, Death
H50	General	Passing under the lifted loads or leaving the load suspended while using load lifting and carrying equipment	Risk of load falling on people	Serious injury, Death
H51	Electric	The presence of uninsulated or damaged electrical cables	Risk of electrocution	Electric shock, Injury, Death
H52	Electric	The presence of obstacles in front of electrical panels	Delay in intervention in case of a possible, Fire	Serious injury, Death
H53	Maintenance and Repair	Using uninsulated or unsuitable tools in electrical work	Exposure to electric shock	Electric shock, Injury, Death
H54	Maintenance and Repair	Deactivation of machine safety equipment and protectors	Contact with rotating parts, electric shock, lack of safety	Serious injury, Death
H55	General	Stacking in inappropriate places in work areas	Overturning of materials on people	Injury, Serious injury
H56	Chemical Substances	Keeping more chemicals than necessary in work areas	Chemical exposure	Poisoning, Injury, Death
H57	Electric	Lack of warnings and markings on electrical panels	Accident due to lack of awareness and unauthorized intervention	Electric shock, Injury, Death
H58	Electric	Exposure of electrical cables to the hot environment	Electrical failure, fire	Electric shock, Injury, Death
H59	Work Equipment	Leaving the compressor air hoses lying around	Trip, fall, injury	Injury, Serious injury
H60	Emergency Situations	Lack of emergency direction signboards	Lack of awareness of possible emergencies	Serious injury, Death

Firstly, sixty hazards, the potential risks associated with these hazards, the source of the hazards, and the type of effects have been identified based on expert opinions.

Then, for each identified hazard, the risk parameters of Probability (P), Frequency (F), and Consequence (C) were rated using the values provided in Tables 4.1, 4.2, and 4.3. The risk score of hazards was calculated by mathematical multiplication of P, F, and C parameters. Risk levels and risk status according to the resulting score were determined according to Table 4.4.

The evaluation and ranking results of hazards in the risk analysis performed with the Fine-Kinney method are shown in Table 5.2.

**Table 5.2** Performing risk analysis with the Fine-Kinney method

<i>Hazard No</i>	<i>Probability (P)</i>	<i>Frequency (F)</i>	<i>Consequence (C)</i>	<i>Risk Score (R)</i>	<i>Risk Situation</i>
<b>H1</b>	3	6	100	1800	Very high risk
<b>H2</b>	3	3	100	900	Very high risk
<b>H3</b>	3	6	40	720	Very high risk
<b>H4</b>	3	2	100	600	Very high risk
<b>H5</b>	3	2	100	600	Very high risk
<b>H6</b>	6	6	15	540	Very high risk
<b>H7</b>	3	3	40	360	High risk
<b>H8</b>	3	3	40	360	High risk
<b>H9</b>	3	1	100	300	High risk
<b>H10</b>	0,5	6	100	300	High risk
<b>H11</b>	3	1	100	300	High risk
<b>H12</b>	6	3	15	270	High risk
<b>H13</b>	6	3	15	270	High risk
<b>H14</b>	6	3	15	270	High risk
<b>H15</b>	6	3	15	270	High risk
<b>H16</b>	3	6	15	270	High risk
<b>H17</b>	3	6	15	270	High risk
<b>H18</b>	3	6	15	270	High risk

Table 5.2 (Continued) Performing risk analysis with the Fine-Kinney method

<i>Hazard No</i>	<i>Probability (P)</i>	<i>Frequency (F)</i>	<i>Consequence (C)</i>	<i>Risk Score (R)</i>	<i>Risk Situation</i>
H19	3	2	40	240	High risk
H20	3	2	40	240	High risk
H21	3	2	40	240	High risk
H22	3	3	15	135	Substantial risk
H23	3	3	15	135	Substantial risk
H24	3	1	40	120	Substantial risk
H25	3	1	40	120	Substantial risk
H26	1	3	40	120	Substantial risk
H27	3	1	40	120	Substantial risk
H28	3	1	40	120	Substantial risk
H29	1	3	40	120	Substantial risk
H30	3	1	40	120	Substantial risk
H31	3	1	40	120	Substantial risk
H32	1	3	40	120	Substantial risk
H33	3	1	40	120	Substantial risk
H34	3	1	40	120	Substantial risk
H35	0,5	6	40	120	Substantial risk
H36	1	3	40	120	Substantial risk
H37	1	1	100	100	Substantial risk
H38	3	2	15	90	Substantial risk
H39	1	6	15	90	Substantial risk
H40	3	3	7	63	Possible risk
H41	3	3	7	63	Possible risk
H42	3	3	7	63	Possible risk
H43	3	3	7	63	Possible risk
H44	0,5	3	40	60	Possible risk
H45	0,5	3	40	60	Possible risk
H46	1	3	15	45	Possible risk

**Table 5.2 (Continued)** Performing risk analysis with the Fine-Kinney method

<i>Hazard No</i>	<i>Probability (P)</i>	<i>Frequency (F)</i>	<i>Consequence (C)</i>	<i>Risk Score (R)</i>	<i>Risk Situation</i>
<b>H47</b>	1	3	15	45	Possible risk
<b>H48</b>	3	1	15	45	Possible risk
<b>H49</b>	1	1	40	40	Possible risk
<b>H50</b>	1	1	40	40	Possible risk
<b>H51</b>	0,5	2	40	40	Possible risk
<b>H52</b>	1	1	40	40	Possible risk
<b>H53</b>	1	1	40	40	Possible risk
<b>H54</b>	0,5	2	40	40	Possible risk
<b>H55</b>	1	2	15	30	Possible risk
<b>H56</b>	0,5	1	40	20	Acceptable risk
<b>H57</b>	0,5	1	40	20	Acceptable risk
<b>H58</b>	0,5	1	40	20	Acceptable risk
<b>H59</b>	1	2	7	14	Acceptable risk
<b>H60</b>	0,5	0,5	40	10	Acceptable risk

From the 60 hazards determined according to the results of risk analysis made with the Fine-Kinney method and obtained in Table 5.2;

- 6 of them are very high risk,
- 15 of them are high risk,
- 18 of them are substantial risk,
- 16 of them are possible risk,
- 5 of them were found to be in the acceptable risk category.

However, the subjectivity in experts' perspectives when performing risk analysis may affect the risk analysis and its results. For example, for the same hazard, one expert may evaluate the consequence (severity) as 40, while a different expert may evaluate it as 15. On the other hand, although the risk scores have the same values, the importance of each P, F, and C scale in different combinations of the danger varies,

which is one of the drawbacks of the current method. Therefore, the proposed fuzzy approach aims to reduce uncertainties and differences in expert opinions.

## 5.2. Application of Fuzzy AHP Method

Within the scope of this study, the method widely used in the literature and developed by Buckley and the application steps of the method are explained.

Firstly, a pairwise comparison matrices of the probability, frequency, and consequence criteria used in risk analysis was created. When creating the matrix, the opinions of the same expert group consisting of five experienced people in the sector were taken and the common view was reflected. In addition, while creating the pairwise comparison matrix, the linguistic terms given in Table 4.5 and their corresponding triangular fuzzy values were used. Then, the weights of the criteria were found by applying each step of the Fuzzy AHP respectively.

The stages of implementation are given below.

- **Step 1: Pairwise comparison matrices**

The pairwise comparison matrix created using linguistic values of probability, frequency, and consequence criteria is given in Table 5.3.

The pairwise comparison matrix made using triangular fuzzy numbers corresponding to linguistic terms is also given in Table 5.4.

**Table 5.3** Pairwise comparison matrices with linguistic values

	Probability	Frequency	Consequence
Probability	Equal (E)	Fairly strong (FS)	Slightly weak (SW)
Frequency	Fairly weak (FW)	Equal (E)	Very weak (VW)
Consequence	Slightly strong (SS)	Very strong (VS)	Equal (E)

**Table 5.4** Pairwise comparison matrices with triangular fuzzy numbers

	Probability	Frequency	Consequence
Probability	(1,1,1)	(1, 3/2, 2)	(2/3, 1, 1)
Frequency	(1/2, 2/3, 1)	(1,1,1)	(2/5, 1/2, 2/3)
Consequence	(1, 1, 3/2)	(3/2, 2, 5/2)	(1,1,1)

- **Step 2. Fuzzy geometric mean matrix**

The fuzzy geometric mean matrix was found using the geometric mean technique with equation (4.3) and the results are shown in Table 5.5.

**Table 5.5** Fuzzy geometric mean value

	Probability	Frequency	Consequence	Fuzzy geometric mean value ( $\tilde{r}_i$ )
Probability	(1,1,1)	(1, 3/2, 2)	(2/3, 1, 1)	(0.87, 1.14, 1.26)
Frequency	(1/2, 2/3, 1)	(1,1,1)	(2/5, 1/2, 2/3)	(0.58, 0.69, 0.87)
Consequence	(1, 1, 3/2)	(3/2, 2, 5/2)	(1,1,1)	(1.14, 1.26, 1.55)

- **Step 3. Fuzzy weights of each criterion**

Fuzzy weights for each criterion are obtained by equation (4.4) and the results are shown in Table 5.6.

**Table 5.6** Fuzzy weights

	Fuzzy geometric mean value ( $\tilde{r}_i$ )	Fuzzy weights ( $\tilde{w}_i$ )
Probability	(0.87, 1.14, 1.26)	(0.236, 0.368, 0.486)
Frequency	(0.58, 0.69, 0.87)	(0.157, 0.223, 0.335)
Consequence	(1.14, 1.26, 1.55)	(0.309, 0.407, 0.598)

- **Step 4. Non-fuzzy weight of parameters**

The best non-fuzzy performance was found using the center of area (COA) method in equation (4.5) and the results are shown in Table 5.7.

**Table 5.7** Non-fuzzy weights

	Fuzzy geometric mean value ( $\tilde{r}_i$ )	Fuzzy weights ( $\tilde{w}_i$ )	Weights ( $w_i$ )
Probability	(0.87, 1.14, 1.26)	(0.236, 0.368, 0.486)	0,363
Frequency	(0.58, 0.69, 0.87)	(0.157, 0.223, 0.335)	0,238
Consequence	(1.14, 1.26, 1.55)	(0.309, 0.407, 0.598)	0,438

Lastly, the weights of the criteria were calculated with the normalization method given in equation (4.6) and are shown in Table 5.8.

**Table 5.8** Weights of the criteria

	Weights ( $w_i$ )	Normalised Weights ( $w$ )
Probability	0,363	0,349
Frequency	0,238	0,229
Consequence	0,438	0,422

The weights of the criteria were found as  $w = (0.349, 0.229, 0.422)$  after normalization.

### 5.3. Application of Fuzzy VIKOR Method

Using the criterion weights obtained from the Fuzzy AHP method, each step of the Fuzzy-VIKOR method was applied respectively and the hazards were prioritized.

Three criteria, namely Probability (P), Frequency (F), and Consequence (C) were used in the application of the Fuzzy VIKOR method, and 60 hazards determined by the Fine-Kinney method were analyzed. A fuzzy decision matrix was created containing the performance values of the hazards under each criterion. The linguistic criteria given in Table 4.5 and the corresponding triangular fuzzy values were used to create the fuzzy decision matrix. The stages of implementation are given below respectively.

- **Step 1: Determine of criteria and alternatives/hazards**

The number of alternatives was considered as  $m$  and the number of criteria was  $n$ .

$n = 3$  (Probability (P), Frequency (F), and Consequence (C))

$m = 60$  (The number of hazards determined by the Fine-Kinney method)

- **Step 2: Creation of fuzzy decision matrix**

The fuzzy decision matrix, created using linguistic terms and the corresponding triangular fuzzy values, is given in Tables 5.9 and 5.10. In this step, while creating the fuzzy decision matrix, the same fuzzy scale used in F-AHP and given in Table 4.5 was used.

**Table 5.9** Fuzzy decision matrix with linguistic terms

Hazards No	Probability	Frequency	Consequence
H1	Fairly strong (FS)	Very strong (VS)	Absolutely strong (AS)
H2	Fairly strong (FS)	Fairly strong (FS)	Absolutely strong (AS)
H3	Fairly strong (FS)	Very strong (VS)	Very strong (VS)
H4	Fairly strong (FS)	Slightly strong (SS)	Absolutely strong (AS)
H5	Fairly strong (FS)	Slightly strong (SS)	Absolutely strong (AS)
H6	Very strong (VS)	Very strong (VS)	Fairly strong (FS)
H7	Fairly strong (FS)	Fairly strong (FS)	Very strong (VS)
H8	Fairly strong (FS)	Fairly strong (FS)	Very strong (VS)
H9	Fairly strong (FS)	Slightly strong (SS)	Absolutely strong (AS)
H10	Equal (E)	Very strong (VS)	Absolutely strong (AS)

**Table 5.9 (Continued)** Fuzzy decision matrix with linguistic terms

<b>Hazards No</b>	<b>Probability</b>	<b>Frequency</b>	<b>Consequence</b>
H11	Fairly strong (FS)	Equal (E)	Absolutely strong (AS)
H12	Very strong (VS)	Fairly strong (FS)	Fairly strong (FS)
H13	Very strong (VS)	Fairly strong (FS)	Fairly strong (FS)
H14	Very strong (VS)	Fairly strong (FS)	Fairly strong (FS)
H15	Very strong (VS)	Fairly strong (FS)	Fairly strong (FS)
H16	Fairly strong (FS)	Very strong (VS)	Fairly strong (FS)
H17	Fairly strong (FS)	Very strong (VS)	Fairly strong (FS)
H18	Fairly strong (FS)	Very strong (VS)	Fairly strong (FS)
H19	Fairly strong (FS)	Slightly strong (SS)	Very strong (VS)
H20	Fairly strong (FS)	Slightly strong (SS)	Very strong (VS)
H21	Fairly strong (FS)	Slightly strong (SS)	Very strong (VS)
H22	Fairly strong (FS)	Fairly strong (FS)	Fairly strong (FS)
H23	Fairly strong (FS)	Fairly strong (FS)	Fairly strong (FS)
H24	Fairly strong (FS)	Equal (E)	Very strong (VS)
H25	Fairly strong (FS)	Equal (E)	Very strong (VS)
H26	Slightly strong (SS)	Fairly strong (FS)	Very strong (VS)
H27	Fairly strong (FS)	Equal (E)	Very strong (VS)
H28	Fairly strong (FS)	Equal (E)	Very strong (VS)
H29	Slightly strong (SS)	Fairly strong (FS)	Very strong (VS)
H30	Fairly strong (FS)	Equal (E)	Very strong (VS)
H31	Fairly strong (FS)	Equal (E)	Very strong (VS)
H32	Slightly strong (SS)	Fairly strong (FS)	Very strong (VS)
H33	Fairly strong (FS)	Equal (E)	Very strong (VS)
H34	Fairly strong (FS)	Equal (E)	Very strong (VS)
H35	Equal (E)	Very strong (VS)	Very strong (VS)
H36	Slightly strong (SS)	Fairly strong (FS)	Very strong (VS)
H37	Slightly strong (SS)	Equal (E)	Absolutely strong (AS)
H38	Fairly strong (FS)	Slightly strong (SS)	Fairly strong (FS)
H39	Slightly strong (SS)	Very strong (VS)	Fairly strong (FS)
H40	Fairly strong (FS)	Fairly strong (FS)	Slightly strong (SS)
H41	Fairly strong (FS)	Fairly strong (FS)	Slightly strong (SS)
H42	Fairly strong (FS)	Fairly strong (FS)	Slightly strong (SS)
H43	Fairly strong (FS)	Fairly strong (FS)	Slightly strong (SS)
H44	Equal (E)	Fairly strong (FS)	Very strong (VS)
H45	Equal (E)	Fairly strong (FS)	Very strong (VS)
H46	Slightly strong (SS)	Fairly strong (FS)	Fairly strong (FS)
H47	Slightly strong (SS)	Fairly strong (FS)	Fairly strong (FS)
H48	Fairly strong (FS)	Equal (E)	Fairly strong (FS)

**Table 5.9 (Continued)** Fuzzy decision matrix with linguistic terms

Hazards No	Probability	Frequency	Consequence
H49	Slightly strong (SS)	Equal (E)	Very strong (VS)
H50	Slightly strong (SS)	Equal (E)	Very strong (VS)
H51	Equal (E)	Slightly strong (SS)	Very strong (VS)
H52	Slightly strong (SS)	Equal (E)	Very strong (VS)
H53	Slightly strong (SS)	Equal (E)	Very strong (VS)
H54	Equal (E)	Slightly strong (SS)	Very strong (VS)
H55	Slightly strong (SS)	Slightly strong (SS)	Fairly strong (FS)
H56	Equal (E)	Equal (E)	Very strong (VS)
H57	Equal (E)	Equal (E)	Very strong (VS)
H58	Equal (E)	Equal (E)	Very strong (VS)
H59	Slightly strong (SS)	Slightly strong (SS)	Slightly strong (SS)
H60	Equal (E)	Slightly weak (SW)	Very strong (VS)

**Table 5.10** Fuzzy decision matrix with triangular fuzzy numbers

Hazards No	Probability	Frequency	Consequence
H1	(1, 3/2, 2)	(3/2, 2, 5/2)	(2, 5/2, 3)
H2	(1, 3/2, 2)	(1, 3/2, 2)	(2, 5/2, 3)
H3	(1, 3/2, 2)	(3/2, 2, 5/2)	(3/2, 2, 5/2)
H4	(1, 3/2, 2)	(1, 1, 3/2)	(2, 5/2, 3)
H5	(1, 3/2, 2)	(1, 1, 3/2)	(2, 5/2, 3)
H6	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(1, 3/2, 2)
H7	(1, 3/2, 2)	(1, 3/2, 2)	(3/2, 2, 5/2)
H8	(1, 3/2, 2)	(1, 3/2, 2)	(3/2, 2, 5/2)
H9	(1, 3/2, 2)	(1, 1, 3/2)	(2, 5/2, 3)
H10	(1, 1, 1)	(3/2, 2, 5/2)	(2, 5/2, 3)
H11	(1, 3/2, 2)	(1, 1, 1)	(2, 5/2, 3)
H12	(3/2, 2, 5/2)	(1, 3/2, 2)	(1, 3/2, 2)
H13	(3/2, 2, 5/2)	(1, 3/2, 2)	(1, 3/2, 2)
H14	(3/2, 2, 5/2)	(1, 3/2, 2)	(1, 3/2, 2)
H15	(3/2, 2, 5/2)	(1, 3/2, 2)	(1, 3/2, 2)
H16	(1, 3/2, 2)	(3/2, 2, 5/2)	(1, 3/2, 2)
H17	(1, 3/2, 2)	(3/2, 2, 5/2)	(1, 3/2, 2)
H18	(1, 3/2, 2)	(3/2, 2, 5/2)	(1, 3/2, 2)
H19	(1, 3/2, 2)	(1, 1, 3/2)	(3/2, 2, 5/2)
H20	(1, 3/2, 2)	(1, 1, 3/2)	(3/2, 2, 5/2)
H21	(1, 3/2, 2)	(1, 1, 3/2)	(3/2, 2, 5/2)
H22	(1, 3/2, 2)	(1, 3/2, 2)	(1, 3/2, 2)

Table 5.10 (Continued) Fuzzy decision matrix with triangular fuzzy numbers

Hazards No	Probability	Frequency	Consequence
H23	(1, 3/2, 2)	(1, 3/2, 2)	(1, 3/2, 2)
H24	(1, 3/2, 2)	(1, 1, 1)	(3/2, 2, 5/2)
H25	(1, 3/2, 2)	(1, 1, 1)	(3/2, 2, 5/2)
H26	(1, 1, 3/2)	(1, 3/2, 2)	(3/2, 2, 5/2)
H27	(1, 3/2, 2)	(1, 1, 1)	(3/2, 2, 5/2)
H28	(1, 3/2, 2)	(1, 1, 1)	(3/2, 2, 5/2)
H29	(1, 1, 3/2)	(1, 3/2, 2)	(3/2, 2, 5/2)
H30	(1, 3/2, 2)	(1, 1, 1)	(3/2, 2, 5/2)
H31	(1, 3/2, 2)	(1, 1, 1)	(3/2, 2, 5/2)
H32	(1, 1, 3/2)	(1, 3/2, 2)	(3/2, 2, 5/2)
H33	(1, 3/2, 2)	(1, 1, 1)	(3/2, 2, 5/2)
H34	(1, 3/2, 2)	(1, 1, 1)	(3/2, 2, 5/2)
H35	(1, 1, 1)	(3/2, 2, 5/2)	(3/2, 2, 5/2)
H36	(1, 1, 3/2)	(1, 3/2, 2)	(3/2, 2, 5/2)
H37	(1, 1, 3/2)	(1, 1, 1)	(2, 5/2, 3)
H38	(1, 3/2, 2)	(1, 1, 3/2)	(1, 3/2, 2)
H39	(1, 1, 3/2)	(3/2, 2, 5/2)	(1, 3/2, 2)
H40	(1, 3/2, 2)	(1, 3/2, 2)	(1, 1, 3/2)
H41	(1, 3/2, 2)	(1, 3/2, 2)	(1, 1, 3/2)
H42	(1, 3/2, 2)	(1, 3/2, 2)	(1, 1, 3/2)
H43	(1, 3/2, 2)	(1, 3/2, 2)	(1, 1, 3/2)
H44	(1, 1, 1)	(1, 3/2, 2)	(3/2, 2, 5/2)
H45	(1, 1, 1)	(1, 3/2, 2)	(3/2, 2, 5/2)
H46	(1, 1, 3/2)	(1, 3/2, 2)	(1, 3/2, 2)
H47	(1, 1, 3/2)	(1, 3/2, 2)	(1, 3/2, 2)
H48	(1, 3/2, 2)	(1, 1, 1)	(1, 3/2, 2)
H49	(1, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
H50	(1, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
H51	(1, 1, 1)	(1, 1, 3/2)	(3/2, 2, 5/2)
H52	(1, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
H53	(1, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
H54	(1, 1, 1)	(1, 1, 3/2)	(3/2, 2, 5/2)
H55	(1, 1, 3/2)	(1, 1, 3/2)	(1, 3/2, 2)
H56	(1, 1, 1)	(1, 1, 1)	(3/2, 2, 5/2)
H57	(1, 1, 1)	(1, 1, 1)	(3/2, 2, 5/2)
H58	(1, 1, 1)	(1, 1, 1)	(3/2, 2, 5/2)
H59	(1, 1, 3/2)	(1, 1, 3/2)	(1, 1, 3/2)
H60	(1, 1, 1)	(2/3, 1, 1)	(3/2, 2, 5/2)

- *Step 3: Defuzzification*

The defuzzification of the elements in the fuzzy decision matrix to crisp values was carried out using equation (4.8) and the results are shown in Table 5.11.

**Table 5.11** Defuzzification

Hazards No	Probability	Frequency	Consequence
H1	1,500	2,000	2,500
H2	1,500	1,500	2,500
H3	1,500	2,000	2,000
H4	1,500	1,083	2,500
H5	1,500	1,083	2,500
H6	2,000	2,000	1,500
H7	1,500	1,500	2,000
H8	1,500	1,500	2,000
H9	1,500	1,083	2,500
H10	1,000	2,000	2,500
H11	1,500	1,000	2,500
H12	2,000	1,500	1,500
H13	2,000	1,500	1,500
H14	2,000	1,500	1,500
H15	2,000	1,500	1,500
H16	1,500	2,000	1,500
H17	1,500	2,000	1,500
H18	1,500	2,000	1,500
H19	1,500	1,083	2,000
H20	1,500	1,083	2,000
H21	1,500	1,083	2,000
H22	1,500	1,500	1,500
H23	1,500	1,500	1,500
H24	1,500	1,000	2,000
H25	1,500	1,000	2,000
H26	1,083	1,500	2,000
H27	1,500	1,000	2,000
H28	1,500	1,000	2,000
H29	1,083	1,500	2,000
H30	1,500	1,000	2,000
H31	1,500	1,000	2,000
H32	1,083	1,500	2,000

Table 5.11 (Continued) Defuzzification

Hazards No	Probability	Frequency	Consequence
H33	1,500	1,000	2,000
H34	1,500	1,000	2,000
H35	1,000	2,000	2,000
H36	1,083	1,500	2,000
H37	1,083	1,000	2,500
H38	1,500	1,083	1,500
H39	1,083	2,000	1,500
H40	1,500	1,500	1,083
H41	1,500	1,500	1,083
H42	1,500	1,500	1,083
H43	1,500	1,500	1,083
H44	1,000	1,500	2,000
H45	1,000	1,500	2,000
H46	1,083	1,500	1,500
H47	1,083	1,500	1,500
H48	1,500	1,000	1,500
H49	1,083	1,000	2,000
H50	1,083	1,000	2,000
H51	1,000	1,083	2,000
H52	1,083	1,000	2,000
H53	1,083	1,000	2,000
H54	1,000	1,083	2,000
H55	1,083	1,083	1,500
H56	1,000	1,000	2,000
H57	1,000	1,000	2,000
H58	1,000	1,000	2,000
H59	1,083	1,083	1,083
H60	1,000	0,944	2,000

- *Step 4: Determination of fuzzy best and fuzzy worst values*

The fuzzy best ( $f_j^*$ ) and fuzzy worst ( $f_j^-$ ) values of all criteria and hazards were found using equations (4.9) and (4.10). The results are shown in Table 5.12.

**Table 5.12** Fuzzy best and fuzzy worst values

	Probability	Frequency	Consequence
$f_j^*$	2,000	2,000	2,500
$f_j^-$	1,000	0,944	1,083

- **Step 5: Calculation of  $S_i$  and  $R_i$  values**

$S_i$  and  $R_i$  values were calculated using equations (4.11) and (4.12). The results are shown in Table 5.13.

At this stage, the criterion weights obtained from the fuzzy AHP method were used. The criteria weights were found as  $w_j = (0.349, 0.229, 0.422)$  with the fuzzy AHP.

**Table 5.13**  $S_i$  and  $R_i$  values

Hazards No	$S_i$	$R_i$
H1	0,1745	0,1745
H2	0,282973684	0,1745
H3	0,323441176	0,1745
H4	0,373368421	0,198868421
H5	0,373368421	0,198868421
H6	0,297882353	0,297882353
H7	0,431914861	0,1745
H8	0,431914861	0,1745
H9	0,373368421	0,198868421
H10	0,349	0,349
H11	0,391447368	0,216947368
H12	0,406356037	0,297882353
H13	0,406356037	0,297882353
H14	0,406356037	0,297882353
H15	0,406356037	0,297882353
H16	0,472382353	0,297882353
H17	0,472382353	0,297882353
H18	0,472382353	0,297882353
H19	0,522309598	0,198868421
H20	0,522309598	0,198868421
H21	0,522309598	0,198868421
H22	0,580856037	0,297882353

**Table 5.13 (Continued)**  $S_i$  and  $R_i$  values

<b>Hazards No</b>	<b><math>S_i</math></b>	<b><math>R_i</math></b>
H23	0,580856037	0,297882353
H24	0,540388545	0,216947368
H25	0,540388545	0,216947368
H26	0,577331527	0,319916667
H27	0,540388545	0,216947368
H28	0,540388545	0,216947368
H29	0,577331527	0,319916667
H30	0,540388545	0,216947368
H31	0,540388545	0,216947368
H32	0,577331527	0,319916667
H33	0,540388545	0,216947368
H34	0,540388545	0,216947368
H35	0,497941176	0,349
H36	0,577331527	0,319916667
H37	0,536864035	0,319916667
H38	0,671250774	0,297882353
H39	0,61779902	0,319916667
H40	0,704973684	0,422
H41	0,704973684	0,422
H42	0,704973684	0,422
H43	0,704973684	0,422
H44	0,606414861	0,349
H45	0,606414861	0,349
H46	0,726272704	0,319916667
H47	0,726272704	0,319916667
H48	0,689329721	0,297882353
H49	0,685805212	0,319916667
H50	0,685805212	0,319916667
H51	0,696809598	0,349
H52	0,685805212	0,319916667
H53	0,685805212	0,319916667
H54	0,696809598	0,349
H55	0,816667441	0,319916667
H56	0,714888545	0,349
H57	0,714888545	0,349
H58	0,714888545	0,349
H59	0,940785088	0,422
H60	0,726941176	0,349

- **Step 6: The calculation of  $S^*$ ,  $S^-$ ,  $R^*$ ,  $R^-$  values**

$S^*$ ,  $S^-$ ,  $R^*$ ,  $R^-$  values were calculated using equations (4.13) and (4.14). The results are shown in Table 5.14.

**Table 5.14**  $S^*$ ,  $S^-$ ,  $R^*$ ,  $R^-$  values

$S^*$	$S^-$	$R^*$	$R^-$
0,1745	0,940785088	0,1745	0,422

- **Step 7: The calculation of  $Q_i$  value**

$Q_i$  value is determined by evaluating  $S^*$ ,  $S^-$ ,  $R^*$ , and  $R^-$  values together. While the  $v$  value expresses the importance of the strategy that provides maximum group benefit,  $1-v$  represents the individual regret value. For the conciliatory majority,  $v \approx 0.5$  can be taken [47].

$Q_i$  values were calculated using equation (4.15) and the results are shown in Table 5.15.

- **Step 8: Ranking the alternatives/hazards according to the  $S_i$ ,  $R_i$  and  $Q_i$  values**

The hazards were ranked according to the  $S_i$ ,  $R_i$  and  $Q_i$  values obtained, and the ranking results are shown in Table 5.15.

The smallest of the  $Q_i$  values indicates the most dangerous situation, while the largest indicates the least dangerous situation.

**Table 5.15**  $Q_i$  values and ranking the according to  $Q_i$  values

<b>Hazards No</b>	<b><math>Q_i</math></b>	<b>Ranking</b>
<b>H1</b>	0	1
<b>H2</b>	0,070778935	2
<b>H3</b>	0,097183919	3
<b>H7</b>	0,167962854	4
<b>H8</b>	0,167962854	4
<b>H4</b>	0,178990514	5
<b>H5</b>	0,178990514	5
<b>H9</b>	0,178990514	5
<b>H11</b>	0,227310129	6
<b>H19</b>	0,276174433	7
<b>H20</b>	0,276174433	7
<b>H21</b>	0,276174433	7
<b>H24</b>	0,324494048	8
<b>H25</b>	0,324494048	8
<b>H27</b>	0,324494048	8
<b>H28</b>	0,324494048	8
<b>H30</b>	0,324494048	8
<b>H31</b>	0,324494048	8
<b>H33</b>	0,324494048	8
<b>H34</b>	0,324494048	8
<b>H6</b>	0,3297641	9
<b>H12</b>	0,400543034	10
<b>H13</b>	0,400543034	10
<b>H14</b>	0,400543034	10
<b>H15</b>	0,400543034	10
<b>H16</b>	0,443625118	11
<b>H17</b>	0,443625118	11
<b>H18</b>	0,443625118	11
<b>H10</b>	0,46638627	12
<b>H22</b>	0,514404052	13
<b>H23</b>	0,514404052	13
<b>H37</b>	0,530213094	14
<b>H26</b>	0,556618079	15
<b>H29</b>	0,556618079	15
<b>H32</b>	0,556618079	15
<b>H36</b>	0,556618079	15
<b>H35</b>	0,56357019	16
<b>H38</b>	0,573386498	17

Table 5.15 (Continued)  $Q_i$  values and ranking the according to  $Q_i$  values

Hazards No	$Q_i$	Ranking
H39	0,583023064	18
H48	0,585182987	19
H49	0,627397014	20
H50	0,627397014	20
H52	0,627397014	20
H53	0,627397014	20
H44	0,634349124	21
H45	0,634349124	21
H46	0,653801999	22
H47	0,653801999	22
H51	0,69333157	23
H54	0,69333157	23
H56	0,705128059	24
H57	0,705128059	24
H58	0,705128059	24
H55	0,712784444	25
H60	0,712992385	26
H40	0,846133373	27
H41	0,846133373	27
H42	0,846133373	27
H43	0,846133373	27
H59	1	28

According to the ranking obtained, the explosion of pressurized gas cylinders/bundles (H1) was found to be the most dangerous situation, while leaving the compressor air hoses lying around (H59) was found to be the least dangerous situation. This was an expected result since the consequence parameter was considered more important than the other parameters.

- **Step 9: Determining the compromise solution**

In the stage of determining the compromise solution, it was examined whether the acceptable advantage and acceptable stability conditions were met. The "Acceptable advantage" condition has been met given in equation (4.16).

## 5.4. Comparison of Classical Fine-Kinney and Proposed Fuzzy-Based Method

A comparison of hazard priorities determined by the hybrid fuzzy AHP and fuzzy VIKOR method and the classical Fine-Kinney method is shown in Table 5.16.

**Table 5.16** Comparison of Fine-Kinney and F-AHP & F-VIKOR ranking

Hazards No	Fine-Kinney Ranking	F-AHP & F-VIKOR Ranking
H1	1	1
H2	2	2
H3	2	3
H4	3	5
H5	3	5
H6	4	9
H7	5	4
H8	5	4
H9	6	5
H10	6	12
H11	6	6
H12	7	10
H13	7	10
H14	7	10
H15	7	10
H16	7	11
H17	7	11
H18	7	11
H19	8	7
H20	8	7
H21	8	7
H22	9	13
H23	9	13
H24	10	8
H25	10	8
H26	10	15
H27	10	8
H28	10	8
H29	10	15
H30	10	8
H31	10	8

**Table 5.16 (Continued)** Comparison of Fine-Kinney and F-AHP & F-VIKOR ranking

<b>Hazards No</b>	<b>Fine-Kinney Ranking</b>	<b>F-AHP &amp; F-VIKOR Ranking</b>
<b>H32</b>	10	15
<b>H33</b>	10	8
<b>H34</b>	10	8
<b>H35</b>	10	16
<b>H36</b>	10	15
<b>H37</b>	11	14
<b>H38</b>	12	17
<b>H39</b>	12	18
<b>H40</b>	13	27
<b>H41</b>	13	27
<b>H42</b>	13	27
<b>H43</b>	13	27
<b>H44</b>	14	21
<b>H45</b>	14	21
<b>H46</b>	15	22
<b>H47</b>	15	22
<b>H48</b>	15	19
<b>H49</b>	16	20
<b>H50</b>	16	20
<b>H51</b>	16	23
<b>H52</b>	16	20
<b>H53</b>	16	20
<b>H54</b>	16	23
<b>H55</b>	17	25
<b>H56</b>	18	24
<b>H57</b>	18	24
<b>H58</b>	18	24
<b>H59</b>	19	28
<b>H60</b>	20	26

As can be seen from Table 5.16, as a result of the analysis, there were differences between the hazard ranking made by the Fine-Kinney method and the ranking made by the proposed integrated F-AHP and F-VIKOR methods. The main reason for this is the lack of sensitivity in classical risk analysis methods and the uncertainty caused by differences in expert opinions. Thanks to the fuzzy logic-based MCDM methods used, precision was increased and uncertainties were tried to be eliminated.

## 5.5. Sensitivity Analysis

The  $Q_i$  value obtained with the Fuzzy VIKOR method was taken into account when hazard priority ranking was made. The smallest of the  $Q_i$  values indicates the most dangerous situation, while the largest indicates the least dangerous situation. Equation 4.15 was used when calculating the  $Q_i$  value. Here, while the  $\nu$  value expresses the importance of the strategy that provides maximum group benefit,  $1-\nu$  represents the individual regret value. The  $\nu$  is the value between 0 and 1. In this study,  $\nu=0,5$  was taken, which is generally used in the literature for the conciliatory majority. On the other hand, calculations were made using the values  $\nu=0,25$ ,  $\nu=0,50$ ,  $\nu=0,75$  and  $\nu=1,00$ , and sensitivity analysis was realized. The  $Q_i$  values calculated for all hazards and all “ $\nu$ ” values are shown in Table 5.17.

**Table 5.17** Comparison of  $Q_i$  values

Hazards No	$Q_i (\nu=0,25)$	$Q_i (\nu=0,50)$	$Q_i (\nu=0,75)$	$Q_i (\nu=1,00)$
H1	0,070201422	0	0,023400474	0
H2	0,027050918	0,070778935	0,081152754	0,108203673
H3	0,118793382	0,097183919	0,169176353	0,194367839
H4	0,202013902	0,178990514	0,240353141	0,25952276
H5	0,202013902	0,178990514	0,240353141	0,25952276
H6	0,44934432	0,3297641	0,257123868	0,161013642
H7	0,154182849	0,167962854	0,275344755	0,335925708
H8	0,154182849	0,167962854	0,275344755	0,335925708
H9	0,202013902	0,178990514	0,240353141	0,25952276
H10	0,606424262	0,46638627	0,353956111	0,227722036
H11	0,257568884	0,227310129	0,27460012	0,283115738
H12	0,484733787	0,400543034	0,36329227	0,302571511
H13	0,484733787	0,400543034	0,36329227	0,302571511
H14	0,484733787	0,400543034	0,36329227	0,302571511
H15	0,484733787	0,400543034	0,36329227	0,302571511
H16	0,506274829	0,443625118	0,427915395	0,388735678
H17	0,506274829	0,443625118	0,427915395	0,388735678
H18	0,506274829	0,443625118	0,427915395	0,388735678
H19	0,250605861	0,276174433	0,38612902	0,453890599
H20	0,250605861	0,276174433	0,38612902	0,453890599
H21	0,250605861	0,276174433	0,38612902	0,453890599
H22	0,541664296	0,514404052	0,534083797	0,530293547

Table 5.17 (Continued) Comparison of  $Q_i$  values

Hazards No	$Q_i (v=0,25)$	$Q_i (v=0,50)$	$Q_i (v=0,75)$	$Q_i (v=1,00)$
H23	0,541664296	0,514404052	0,534083797	0,530293547
H24	0,306160844	0,324494048	0,420376	0,477483577
H25	0,306160844	0,324494048	0,420376	0,477483577
H26	0,601035215	0,556618079	0,550807786	0,525694071
H27	0,306160844	0,324494048	0,420376	0,477483577
H28	0,306160844	0,324494048	0,420376	0,477483577
H29	0,601035215	0,556618079	0,550807786	0,525694071
H30	0,306160844	0,324494048	0,420376	0,477483577
H31	0,306160844	0,324494048	0,420376	0,477483577
H32	0,601035215	0,556618079	0,550807786	0,525694071
H33	0,306160844	0,324494048	0,420376	0,477483577
H34	0,306160844	0,324494048	0,420376	0,477483577
H35	0,655016221	0,56357019	0,49973199	0,422089874
H36	0,601035215	0,556618079	0,550807786	0,525694071
H37	0,587832723	0,530213094	0,511200309	0,472884101
H38	0,571155519	0,573386498	0,622557465	0,648258438
H39	0,614237708	0,583023064	0,590415263	0,578504041
H40	0,923066687	0,846133373	0,76920006	0,692266746
H41	0,923066687	0,846133373	0,76920006	0,692266746
H42	0,923066687	0,846133373	0,76920006	0,692266746
H43	0,923066687	0,846133373	0,76920006	0,692266746
H44	0,690405689	0,634349124	0,605900392	0,563647744
H45	0,690405689	0,634349124	0,605900392	0,563647744
H46	0,649627175	0,653801999	0,696583665	0,72006191
H47	0,649627175	0,653801999	0,696583665	0,72006191
H48	0,577053763	0,585182987	0,640252198	0,671851416
H49	0,636424683	0,627397014	0,656976188	0,66725194
H50	0,636424683	0,627397014	0,656976188	0,66725194
H51	0,719896911	0,69333157	0,69437406	0,681612635
H52	0,636424683	0,627397014	0,656976188	0,66725194
H53	0,636424683	0,627397014	0,656976188	0,66725194
H54	0,719896911	0,69333157	0,69437406	0,681612635
H55	0,679118398	0,712784444	0,785057333	0,838026801
H56	0,725795156	0,705128059	0,712068794	0,705205613
H57	0,725795156	0,705128059	0,712068794	0,705205613
H58	0,725795156	0,705128059	0,712068794	0,705205613
H59	1	1	1	1
H60	0,729727319	0,712992385	0,723865283	0,720934265

Lastly, the hazard priority rankings of  $Q_i$  values calculated for all  $v$  values are given in Table 5.18.

**Table 5.18** Priority rankings of hazards according to  $Q_i$  values

Hazards No	$Q_i (v=0,25)$	$Q_i (v=0,50)$	$Q_i (v=0,75)$	$Q_i (v=1,00)$
H1	2	1	1	1
H2	1	2	2	2
H3	3	3	3	4
H4	5	5	4	6
H5	5	5	4	6
H6	9	9	5	3
H7	4	4	7	9
H8	4	4	7	9
H9	5	5	4	6
H10	17	12	8	5
H11	7	6	6	7
H12	10	10	9	8
H13	10	10	9	8
H14	10	10	9	8
H15	10	10	9	8
H16	11	11	12	10
H17	11	11	12	10
H18	11	11	12	10
H19	6	7	10	12
H20	6	7	10	12
H21	6	7	10	12
H22	12	13	15	16
H23	12	13	15	16
H24	8	8	11	14
H25	8	8	11	14
H26	16	15	16	15
H27	8	8	11	14
H28	8	8	11	14
H29	16	15	16	15
H30	8	8	11	14
H31	8	8	11	14
H32	16	15	16	15
H33	8	8	11	14
H34	8	8	11	14

**Table 5.18 (Continued)** Priority rankings of hazards according to  $Q_i$  values

Hazards No	$Q_i$ ( $\nu=0,25$ )	$Q_i$ ( $\nu=0,50$ )	$Q_i$ ( $\nu=0,75$ )	$Q_i$ ( $\nu=1,00$ )
H35	21	16	13	11
H36	16	15	16	15
H37	15	14	14	13
H38	13	17	19	19
H39	18	18	17	18
H40	27	27	26	23
H41	27	27	26	23
H42	27	27	26	23
H43	27	27	26	23
H44	23	21	18	17
H45	23	21	18	17
H46	20	22	23	25
H47	20	22	23	25
H48	14	19	20	21
H49	19	20	21	20
H50	19	20	21	20
H51	24	23	22	22
H52	19	20	21	20
H53	19	20	21	20
H54	24	23	22	22
H55	22	25	27	27
H56	25	24	24	24
H57	25	24	24	24
H58	25	24	24	24
H59	28	28	28	28
H60	26	26	25	26

As a result of the sensitivity analysis, H2 was found to be the most dangerous situation according to the  $\nu=0,25$  value, while H1 was found to be the most dangerous situation according to  $\nu=0,50$ ,  $\nu=0,75$ , and  $\nu=1,00$  values.

Otherwise, H59 was found to be the least dangerous situation in all  $\nu$  values.

# CHAPTER 6

## CONCLUSION AND DISCUSSION

Today, ensuring occupational health and safety has become quite important issue to determine and prevent existing or potential dangers in businesses. Work accidents and occupational diseases occurring in companies cause serious labor and cost losses. This situation emphasizes the increasing importance of occupational health and safety studies. Therefore, the importance given by companies to risk analysis and risk assessment studies to ensure occupational health and safety is also increasing.

Especially in sectors such as the Defense Industry, which have strategic importance, an effective risk analysis should be conducted to determine and prevent existing or potential hazards, and protective and preventive measures should be taken. However, while many methods are employed in risk analysis, traditional approaches sometimes lack the necessary sensitivity. In such cases, hybrid risk analysis methods can be utilized to achieve more accurate assessments. Fuzzy logic-based multi-criteria decision-making (MCDM) methods can offer an effective way to conduct more comprehensive a risk analysis that can account for uncertainties.

In this thesis, the aim was to increase the effectiveness of risk management and decision-making processes by integrating fuzzy logic-based multi-criteria decision-making (MCDM) methods with the Fine-Kinney Method, a risk analysis technique. Owing to this integration, hazards and risks were better understood, aiming for more effective measures to be taken. In this context, a fuzzy approach using linguistic terms and triangular numbers has been proposed to reduce the uncertainties and differences in expert opinions. Specifically, the Fuzzy Analytic Hierarchy Process (AHP) and Fuzzy VIKOR methods were utilized to overcome the challenges posed by uncertainties and subjective evaluations in the processes of identifying and prioritizing risks, thereby achieving more objective and reliable results. These methods provided decision-makers with the capability to make more effective and informed decisions by considering the complexity and multidimensionality of risks.

Firstly, the possible hazards were determined by taking expert opinions, and the risk scores of these hazards were obtained with the Fine-Kinney risk analysis method. While determining the hazards, five experts experienced in the sector were consulted and the consensus was reflected. For the sixty hazards determined, the Probability (P), Frequency (F), and Consequence (C) risk parameters in the Fine-Kinney method were taken into account separately. In the next phase, the values obtained as a result of the pairwise comparison of each criterion (Probability, Frequency, and Consequence) were expressed as triangular fuzzy numbers, and the weights of the criteria were found by applying each step of Buckley's Fuzzy AHP method respectively. When creating the matrix in the F-AHP method, the opinions of the same expert group consisting of five experienced people in the sector were taken and the common view was reflected. Then, hazards were prioritized and ranked with the Fuzzy-VIKOR method using the obtained criteria weights. Lastly, sensitivity analysis was performed and the change in the ranking of alternatives according to different  $v$  values was examined. The proposed two-stage fuzzy multi-criteria approach enabled a more accurate and comprehensive assessment of occupational health and safety risks in the defense industry sector, thereby assisting in identifying more effective control measures for the hazards.

As a result of the analyses conducted within the scope of this study, differences were observed between the hazard rankings made with the traditional Fine-Kinney method and the hazard rankings made with the proposed integrated fuzzy MCDM approach. The primary reason for this discrepancy is the lack of sensitivity and the presence of uncertainties in the traditional Fine Kinney method, which does not assign any weight values to the criteria. Since the criteria are weighted and used based on fuzzy logic with the integrated F-AHP and F-VIKOR methods used in the study, sensitivity was increased and uncertainties were tried to be eliminated. Therefore, differences were observed in the hazard priority rankings between the traditional method and integrated fuzzy methods.

Consequently, in the literature review conducted, it is observed that methodological studies on risk analysis and management in the defense industry are limited. It has been observed that comprehensive approaches, especially those that take into account uncertainties and subjective evaluations, have not been sufficiently addressed in this

sector. This thesis study was aimed to provide an original contribution to address this deficiency and fill the gap. In this context, thanks to the integrated use of fuzzy logic and MCDM methods proposed in the thesis, the potential to develop more effective risk management strategies in critical areas such as the defense sector has been offered. In addition, there are not many studies conducted within the framework of risk assessment by integrating the fuzzy logic-based F-AHP and F-VIKOR methods with the Fine-Kinney Method, which is a risk analysis technique. Therefore, this study makes an important contribution to the existing literature on risk analysis and fuzzy logic integration in the defense industry.

Moreover, this thesis has provided a new perspective on risk analysis processes in the defense industry and offered a more reliable and comprehensive risk management approach through the integration of fuzzy multi-criteria decision-making methods. With this integrated approach, it was aimed to significantly improve the accuracy and reliability of risk assessments. The findings of this study contribute significantly to enhancing the success and safety of defense industry projects and it sheds light on future research and applications in this field. In future studies, broader application and further development of these approaches will help achieve significant advancements in the field of risk management. Thus, it was objective to serve as a valuable reference for both academic research and practical applications in the defense industry.

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