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# Risk assessment of Flyrock in Surface Mines using a FFTA-MCDM Combination

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*Flyrock*

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*MCDM*

***Abstract***

The drilling and blasting method is the first choice for rock breakage in surface or underground mines due to its high flexibility against variations and low investment costs. However, any method has its own advantages and disadvantages. The flyrock phenomenon is one of the drilling and blasting disadvantages that the mining engineers have always been faced with in the surface mine blasting operations. Flyrock may lead to fatality and destroy mine equipment and structures, and so its risk assessment is very essential. For a flyrock risk assessment, the causing events that lead to flyrock along with their probabilities and severities should be identified. For this aim, a combination of the fuzzy fault tree analysis and multi-criteria decision-making methods are used. Based on the results obtained, the relevant causing events of flyrock in surface mines can be categorized into three major groups: design error, human error, and natural error. Finally, using the obtained probabilities and severities for these three groups, the risk matrix is constructed. Based on the risk matrix, the risk numbers of flyrock occurrence due to the design errors, human errors, and natural influence are 12, 6, and 2, respectively. Hence, in order to minimize the flyrock risk, it is very vital for the engineers to select appropriate values for the design events of blasting pattern such as burden, spacing, delays, and hole diameter.

## 1. Introduction

In mining processes, drilling and blasting is a major technique available for rock breakage due to the low initial investment and high flexibility against ground condition variation in a surface or underground mine. However, in spite of the drilling and blasting advantages, this method has many negative consequences. One of these negative consequences is known as flyrock, which is one of the most hazardous phenomena in the drilling and blasting operation of surface mines. This phenomenon is defined as driving rock fragments beyond a desired area, which can result in human injuries, fatalities, and structure damages [1]. Based on the statistical data in China, flyrock is the reason of about 27% of surface mine disaster events [2]. There can be many reasons for the flyrock phenomenon occurring ranging from deviations in the blast pattern design or their implementation, explosive use, and known or unknown ground conditions. Generally, the causing factors of flyrock can be divided into the controllable and uncontrollable factors. The controllable factors are the results of the blasting design and implementation. Insufficient stemming, short inter-row delay, inadequate burden, and inaccurate drilling are a number of controllable causing factors of flyrock. The uncontrollable factors are restricted to the blasting operation by natural ground conditions like the geological and geotechnical features [1, 3, 4].

Flyrock has three initiation mechanisms that are named as rifling, cratering, and face bursting. As it can be seen in Figure 1, in the rifling mechanism, due to the insufficient stemming materials, blast gases move along the path of least resistance, and then the stemming materials are ejected vigorously into the longer distances. The blast hole collar regions usually contain loosened rocks due to a

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previous blasting. In this region, blast gases easily move into the air and propagate cracks and produce cratering flyrock (Figure 1). The face bursting mechanism occurs when the explosive charges are adjacent to the major geological structures or zones of weakness. The high-pressure gases of the explosives move along the least resistance paths and generate flyrock (Figure 1) [3, 4].

From the flyrock consequences and mine safety viewpoint, risk management of flyrock is very crucial in the surface mines that have been suffering from flyrock. The concept of risk has a long history and goes back to 2400 years ago when the Athenians offered their capacity of assessing risk before making decisions [5]. Risk management consists of risk identification, assessment, and prioritization. Risk identification is the first step taken to describe the possible negative effects of the system events; risk assessment is the measures based on probability of risk event, and make decisions on the treatment plan according to the possible risk size and degree of loss [6], and risk prioritization is fundamental for the definition of the actions that will be undertaken to mitigate or eliminate risks [7].

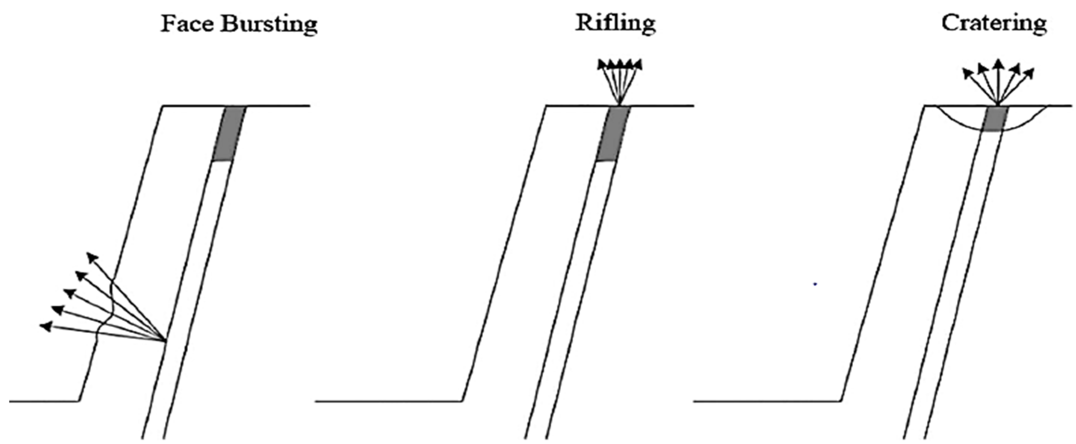


**Figure 1. Schematic view of flyrock mechanisms [4].**

In the recent years, most of the flyrock-related works have been about introducing predictive models using statistical or soft computing methods for the flyrock distance (e.g. [1, 3, 8-13]).

Here are descriptions about the works that have been done in the field of flyrock risk assessment. According to the reviewed works, fault tree analysis (FTA) has a specific role in a flyrock risk assessment. Paithankar [14] has analyzed and identified the iron ore mine risks. Based on the results obtained, the human error, burden, spacing, hole diameter, drilling, specific charge quality, blasting, geologic anomaly, and wind are the most important flyrock events in iron ore mines. Zhou *et al*. [15] have used FTA to analyze the risk of flyrock phenomenon in a blasting operation. In this work, using the minimum cut set method, the most critical and vulnerable component in the flyrock accident was identified. This work showed that geologic anomaly, unexpected wind, no supervision, drilling deviation, wrong charging order, poor stemming, wrong firing order, small blast area, no shielding of operator, blur alerting sign, no guard, no alarming, no checkup, error estimation of terrain, blast hole overloading, unreasonable burden, large hole distance, short stemming length, and improper delay time were intended as events for flyrock. It was found that strengthening the operation supervision was one of the most important procedures to be performed in blasting .

Wang *et al*. [16] have used FTA to analyze the risk of flyrock in the cooling tower demolition project in the Guiyang Power Plant. This work indicated that there were a variety of reasons such as the management, technical, and operational issues that could cause the generation of flyrock. Moreover, these tree events can be used as a direct output event, for example, stemming, protection, burden, unclear alert command, and drilling deviation. Based on the results obtained, the highest probability of flying rock was caused by a large quantity of maximum priming charge.

Although these works have provided a significant role for risk assessment of fly rock in surface mines, the most shortcoming of these works is the calculation risk number of fly rock in surface mines. In addition, no scientific or systematic approach was applied to calculate the probabilities and severities quantitatively in surface mines. For this purpose, using a combination of the fuzzy fault tree analysis and multi-criteria decision-making methods, the flyrock risk assessment has been performed for the drilling and blasting operations in surface mines.

## 2. Methods and materials

The present work aimed at risk assessment of flyrock in surface mines in order to calculate the risk number and minimize the risk of flyrock. Figure 2 illustrates the framework for the proposed approach. As shown in this figure, using the literature review and experts' recommendations, our experience and analysis of the risk levels of flyrock and its events were identified. Then the probabilities of events and flyrock occurrence were calculated using the fuzzy fault tree analysis (FFTA). After that, by combining the decision-making trial and evaluation laboratory (DEMATEL) method and the fuzzy analytic network process (FANP) technique, a hybrid multiple-criteria decision-making model was developed to propose the flyrock consequence severities. These methods are based on the experts' surveys. In this work, DEMATEL was applied to evaluate the interdependence among the effective events. The outer dependencies as well as the weighting of clusters were determined using the fuzzy ANP procedure through a pairwise comparison. Finally, the number of risk events was calculated by multiplying the probability and severity of the consequence.

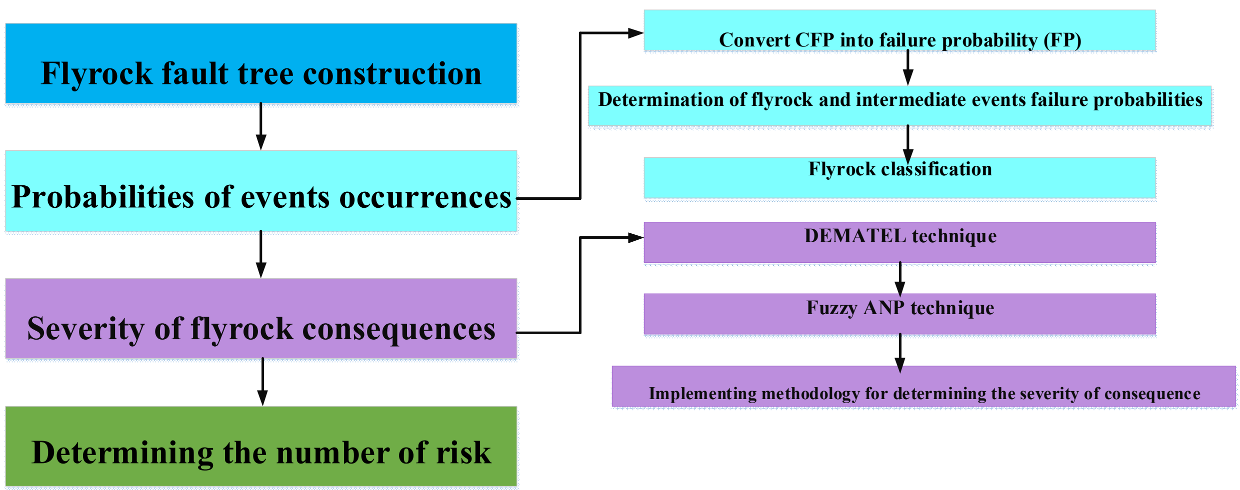


**Figure 2. Framework of risk assessment of flyrock in surface mines.**

### 2.1. Flyrock fault tree construction

The fault tree analysis (FTA), originally developed in 1962 at the Bell laboratories by Watson is a top down deductive failure analysis, series the basic events (BEs) combined with logical gates to analyze the probability of an undesirable event (top event, TE). FTA involves the development of a fault tree of the pathways within a system that can lead to an undesirable event [17]. A schematic view of the fault tree is shown in Figure 3. In a fault tree, a BE does not require any development; however, intermediate events (IEs) are the results of their lower level events and the reason for their upper level events [18]. In an AND gate, the output event occurrence is only dependent on all the input event occurrences; and in an OR gate, the output event occurs at least by one input event occurrence [17].

Thus it is necessary to identify the main components and events of flyrock in surface mines. For this purpose, as mentioned earlier, the literature, recommendations of the experts, and our knowledge and analyses were used.

The flyrock phenomenon can be divided into three categories: design error, human error, and natural influences, which are described as follow:

**Design error:** Mistakes in the design of blasting patterns can cause big deviations from expectation, and result in a flyrock occurrence. There are many design errors such as improper delay time, spacing, burden, and charge designing.

**Human error:** As all the designs and operations are implemented by the humans, these kinds of errors are inevitable. For example, no alarming, and not enough blasting operator skill and experience are some of these errors.

**Natural influences:** A sudden change in the blasting environment (e.g. mismatch between the explosive energy and the resistance of the rock, unexpected wind) during rock blasting can cause problems such as flyrock.

According to the above-mentioned categories, the intermediate and basic events of the flyrock phenomenon are shown in Table 1. The designed fault tree is also plotted, as shown in Figure 4.

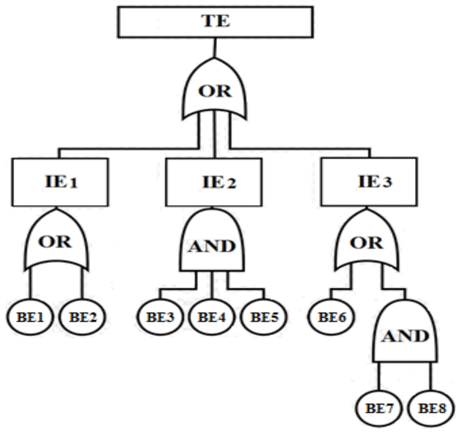

**Figure 3. Scematic view of fault tree [17].**

## 2.2. Probabilities of events occurrences

In the conventional FTA, the probabilities of basic events are exact values. However, the lack of data and ambiguous information lead to difficulties in the determination of the exact probability values. In order to overcome this issue, the fuzzy set theory has been combined with FTA [19]. The top event probability can be obtained by estimating the basic event probabilities [20]. In a fuzzy fault tree analysis (FFTA), the basic event probabilities can be estimated using a combination of the experts' linguistic judgments and the fuzzy logic [21]. Therefore, in this work, 10 experts were considered for the questionnaire survey, and their linguistic judgments were transformed to the fuzzy number using Figure 5 and Table 2.

**Table 1. Details of flyrock fault tree.**

| Symbol | Name | Event type |
|---|---|---|
| TE | Flyrock | Top |
| IE1 | Design error | Intermediate |
| IE2 | Human error | Intermediate |
| IE3 | Natural influences | Intermediate |
| IE4 | Operation error | Intermediate |
| IE5 | Lack of security | Intermediate |
| BE1 | Improper delay time | Basic |
| BE2 | Amount of burden | Basic |
| BE2 | Amount of spacing | Basic |
| BE3 | Hole diameter | Basic |
| BE4 | Drilling | Basic |
| BE5 | Specific charge quality | Basic |
| BE6 | Hole length | Basic |
| BE7 | Stemming length | Basic |
| BE8 | Hole slope | Basic |
| BE9 | Hole deviation | Basic |
| BE10 | No alarming | Basic |
| BE11 | Blasting operator skill | Basic |
| BE12 | Experience | Basic |
| BE13 | No shielding of operator | Basic |
| BE14 | Precision in drilling operations | Basic |
| BE15 | Lack of supervision and technical inspection of the supervisor | Undeveloped |
| BE16 | Small blast area | Basic |
| BE17 | Geologic anomaly | Basic |
| BE18 | Unexpected wind | Basic |
| BE19 | Impossible to predict natural effects | Basic |
| BE20 | Estimation of mistake of natural complications | Undeveloped |

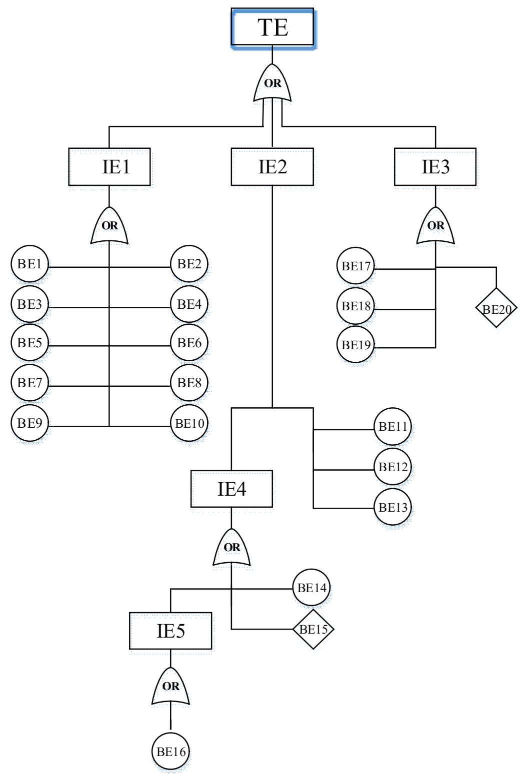


**Figure 4. Flyrock fault tree.**

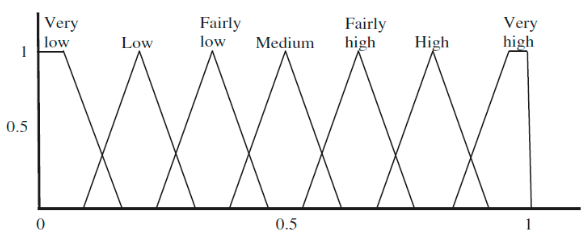


**Figure 5. Fuzzy numbers [21].**

**Table 2. Fuzzy numbers of linguistic terms [19].**

| Linguistic terms | Symbol | Fuzzy number |
|---|---|---|
| Very low | VL | (0,0,0.1,0.2) |
| Low | L | (0.1,0.25,0.25,0.4) |
| Medium | M | (0.3,0.5,0.5,0.7) |
| High | H | (0.6,0.75,0.75,0.9) |
| Very high | VH | (0.8,0.9,1,1) |

In order to estimate the basic event failure possibility, at first, each expert was weighted using Table 3. After that, fuzzy number aggregations were done using Equation (1). In this equation, $A_{ij}$ is the fuzzy number of the i$^{th}$ basic event given by the j$^{th}$ expert judgment, m is the number of basic events, n is the number of experts, $W_j$ is a j$^{th}$ experts' normalized weight, and finally, $M_i$ is the aggregated fuzzy number of the i$^{th}$ basic event. Then using Equation (2), the fuzzy numbers (e.g. a = ($a_1$, $a_2$, $a_3$, $a_4$)) were deffuzified and converted to the crisp values named as the crisp failure possibilities (CFPs) [17, 19, 22, 23]. The final experts' weights and the aggregation of fuzzy numbers with crisp failure possibilities of basic events are shown in Tables 4 and 5, respectively.

$$M_i = \sum_{j=1}^{n} W_j A_{ij} \qquad (i = 1, 2, 3, ..., m) \tag{1}$$

$$CFP = \frac{1}{3}\frac{(a_4 + a_3)^2 - a_4 a_3 - (a_1 + a_2)^2 + a_1 a_2}{(a_4 + a_3 - a_2 - a_1)} \tag{2}$$

**Table 3. Weighting score according to the experts' trait [22].**

| Constitution | Classification | Score |
|---|---|---|
| Title | Professor, Chief Engineer, Director | 4 |
| | Asst. Prof., Manager, Factory Inspector | 3 |
| | Supervisors, Foreman, Graduate Apprentice | 2 |
| | Operator | 1 |
| Experience | Greater than 30 years | 5 |
| | 20-30 | 4 |
| | 10-20 | 3 |
| | 5-10 | 2 |
| Education | PhD | 5 |
| | Master | 4 |
| | Bachelor | 3 |
| | ITI | 2 |
| | Secondary School | 1 |
| Age | Greater than 50 | 4 |
| | 40-50 | 3 |
| | 30-40 | 2 |
| | Less than 30 | 1 |

**Table 4. Experts' weighting based on their traits.**

| Expert number | Title | Experience (Year) | Education | Weight |
|---|---|---|---|---|
| 1 | Director | 15 | PhD | 0.0993 |
| 2 | Director | 20 | Bachelor | 0.0973 |
| 3 | Director | 10 | Bachelor | 0.0910 |
| 4 | Supervisor | 10 | PhD | 0.0990 |
| 5 | Director | 26 | Master | 0.1034 |
| 6 | foreman | 7 | PhD | 0.1124 |
| 7 | Manager | 8 | Bachelor | 0.1020 |
| 8 | Director | 13 | PhD | 0.0993 |
| 9 | Supervisor | 10 | Master | 0.0964 |
| 10 | Director | 17 | Master | 0.0999 |

### 2.2.1 Conversion of CFP to failure probability (FP)

In a fault tree, the probabilities of BEs are essential for a TE occurrence analysis, and their possibilities are not useful. Equation (3) has been used for converting the crisp failure possibilities of BEs into the failure probabilities by many researchers. This equation was introduced by Onisawa [24]. The Results of determination of failure probabilities of flyrock basic events are illustrated in Table 6.

$$FP = \begin{cases} 1/10^k & CFP \neq 0 \\ 0 & CFP = 0 \end{cases}, \quad k = 2.301 \times \left[\frac{1-CFP}{CFP}\right]^{1/3} \tag{3}$$

### 2.2.2 Determination of flyrock and intermediate event failure probabilities

Using the BE failure probabilities, the failure probabilities of flyrock as top events and intermediate events were estimated. Therefore, using Equations (4) and (5) [25] for "AND" and "OR" gate events, respectively, the top and intermediate event probabilities were determined. The results are presented in Table 6.

$$P(E_0) = \prod_{i=1}^{m} P(E_i) \tag{4}$$

$$P(E_0) = 1 - \prod_{i=1}^{m} (1 - P(E_i)) \tag{5}$$

**Table 5. Failure possibilities and probabilities of flyrock basic events.**

| Symbol | Aggregated fuzzy number | CFP | FP |
|---|---|---|---|
| BE1 | (0.66, 0.77, 0.84, 0.87) | 0.784 | 0.032 |
| BE2 | (0.66, 0.77, 0.82, 0.87) | 0.777 | 0.030 |
| BE3 | (0.58, 0.70, 0.75, 0.82) | 0.709 | 0.019 |
| BE4 | (0.49, 0.62, 0.64, 0.76) | 0.626 | 0.012 |
| BE5 | (0.42, 0.54, 0.55, 0.66) | 0.540 | 0.007 |
| BE6 | (0.54, 0.66, 0.70, 0.78) | 0.668 | 0.015 |
| BE7 | (0.33, 0.50, 0.50, 0.66) | 0.498 | 0.005 |
| BE8 | (0.56, 0.67, 0.73, 0.79) | 0.684 | 0.017 |
| BE9 | (0.53, 0.66, 0.69, 0.78) | 0.663 | 0.015 |
| BE10 | (0.50, 0.63 ,0.66, 0.77) | 0.639 | 0.013 |
| BE11 | (0.58, 0.71, 0.75, 0.83) | 0.716 | 0.020 |
| BE12 | (0.59, 0.71, 0.75, 0.84) | 0.721 | 0.021 |
| BE13 | (0.45, 0.60, 0.61, 0.75) | 0.604 | 0.010 |
| BE14 | (0.47, 0.62, 0.62, 0.77) | 0.616 | 0.011 |
| BE15 | (0.41, 0.54, 0.57, 0.67) | 0.546 | 0.007 |
| BE16 | (0.32, 0.41, 0.41, 0.50) | 0.407 | 0.002 |
| BE17 | (0.50, 0.63, 0.66, 0.77) | 0.638 | 0.012 |
| BE18 | (0.38, 0.50, 0.50, 0.62) | 0.499 | 0.005 |
| BE19 | (0.44, 0.59, 0.61, 0.75) | 0.598 | 0.009 |
| BE20 | (0.56, 0.69, 0.72, 0.82) | 0.694 | 0.017 |

**Table 6. Failure probabilities of top and intermediate events.**

### 2.2.3. Flyrock classification

In this section, the risks of flyrock occurrence are classified. For this purpose, Table 7 is presented using the mean and standard deviation of the main flyrock intermediate event probabilities (design error, human error, and natural influences). The classification results are shown in Table 8. As it can be seen, the occurrence probability of flyrock due to the design error is more possible than the human and natural influences.

**Table 7. Ranking risk of flyrock occurrence.**

| Probability (%) | Probability level | Rating |
|---|---|---|
| ≥23 | Very likely | 5 |
| 17.4 – 23 | Likely | 4 |
| 11.7 -17.4 | Possible | 3 |
| 6 - 11.7 | Unlikely | 2 |
| ≤6 | Very unlikely | 1 |

**Table 8. Ranking probability of the main flyrock intermediate events.**

| Symbol | Name | Probability (%) | Rate |
|---|---|---|---|
| $IE_1$ | Design error | 15.4 | 3 |
| $IE_2$ | Human error | 6.9 | 2 |
| $IE_3$ | Natural influences | 4.4 | 1 |

### 2.3. Severity of flyrock consequences

By combination of decision-making trial and evaluation laboratory (DEMATEL) and fuzzy ANP, a hybrid MCDM model was used to determine the consequence severity of the risks of the main flyrock intermediate events. These methods are based on the experts' survey, and subsequently, involve uncertainty. In this work, the DEMATEL method was applied to evaluate the inner-dependencies between the main flyrock intermediate events. The outer-dependencies as well as the weighting of clusters were determined using the FANP procedure through a pairwise comparison.

### 2.3.1. DEMATEL technique

DEMATEL is based upon the graph theory, introduced for the first time in the late 1971 in Geneva Research Center by Fontela and Gabus for the study of very complex structure systems [26-29]. It is a practical and useful method for visualizing the structure of complicated relationships with matrices or directed graphs. In order to implement this method, 7 steps must be carried out, as follow [30, 31]:

***Step 1: Determining effective events in system.*** In this step, the main effective events are determined using the brain storming, literature review, etc. Therefore, as stated in the previous sections, the design error, human error, and natural influences are considered as the effective events.

***Step 2: Establishing pairwise comparison matrix.*** For this purpose, a square matrix is constructed

(Table 10). In this matrix, the effective events are put in rows and columns. Then a questionnaire survey is done to indicate the direct influence of each event on the others according to the 0 to 4 scale.

**Table 9. Matrix for the DEMATEL method.**

| | Design error ($c_1$) | Human error ($c_2$) | Natural influences ($c_3$) |
|---|---|---|---|
| Design error ($c_1$) | 0 | | |
| Human error($c_2$) | | 0 | |
| Natural influences ($c_3$) | | | 0 |

***Step 3: Estimating average matrix.*** The average matrix (A) is the average of the pairwise comparison matrix. The (i,j) element of matrix A is $a_{ij}$, which can be estimated as follows:

$$a_{ij} = \frac{1}{h}\sum_{k=1}^{h} x_{ij}^{k} \tag{6}$$

***Step 4: Calculating initial direct influence matrix.*** The initial direct influence matrix (D) is obtained through normalizing matrix "A" using Equations (7) and (8).

$$D = \frac{A}{S} \tag{7}$$

where S is a constant, which can be calculated as follows:

$$s = \max\left(\max_{1\le i\le n}\sum_{j=1}^{n} a_{ij}, \max_{1\le j\le n}\sum_{i=1}^{n} a_{ij}\right) \tag{8}$$

***Step 5: Calculating total relation matrix.*** Based on the graph theory, the sum of the direct and indirect influences that vertices of a graph exert on each other, with considering all feedback, is the sum of the terms of an infinite geometric series. Therefore, the total relation matrix (T) denotes the total indirect and direct relation, calculated as follows:

$$T = \sum_{m=1}^{\infty} D^{i} = D\left(1-D\right)^{-1} \tag{10}$$

### 2.3.2. Fuzzy ANP technique

ANP is the general form and extension of the AHP method, presented by Saaty [32]. ANP provides a general framework to deal with a complex real problem in which there are independences within a cluster (inner-dependency) and among different clusters (outer-dependency). In fact, ANP incorporates a network to consider the feedback relationships among the criteria without the need to determine the levels as the hierarchy in AHP. Thus it is utilized in cases where interactions exist among the system elements form a network structure. According to Saaty [32], ANP is applied for prediction and representation of the competitors with their interactions and relative strengths in making decision. ANP is used in the deterministic and fuzzy forms; in this work, the fuzzy form was applied. In general, FANP has two main steps, as follow [33]:

***Step 1: Problem network establishment.*** At first, it is necessary to state the problem clearly and to construct its corresponding network accordingly. For this purpose, the decision maker's opinion through brain storming or other appropriate methods such as DEMATEL is incorporated.

***Step 2: Forming supermatrix.*** In order to form the supermatrix, the system criteria are compared by determining the importance of each criterion in comparing with another criterion with respect to its controlled criteria. The relative importance is determined using a scale of 1 to 9 that represent the equal importance with the extreme importance. The general form of supermatrix is shown in Figure 6.

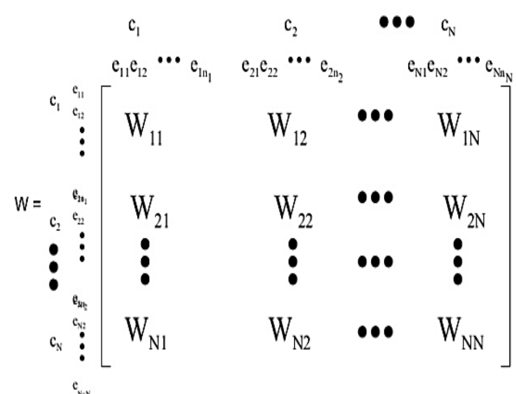

**Figure 6. General form of supermatrix [33].**

where $C_m$ denotes the $m^{th}$ cluster, $e_{mn}$ denotes the nth element in the $m^{th}$ cluster, and matrix $W_{ij}$ is the principal eigenvector compared to the jth and ith clusters.

Subsequently, the weighted supermatrix is derived by equating the normalized summation of each column to 1. The weighted supermatrix is raised to limiting powers as Equation (11) to calculate the weights and overall priorities. In this equation, W is the supermatrix.

$$\lim_{k\to\infty} W^{k} \tag{11}$$

### 2.3.3. Implementing methodology for determining severity of consequence

In order to implement the method for determining the severity of consequence, the weight of each event is required to be calculated as effective events possessing various levels of significance. Therefore, the supermatrix is established as displayed in Figure 7.

In the supermatrix, $W_{22}$ and $W_{33}$ are the inner-dependency matrices that have been assessed using the DEMATEL technique (Figure 8). $W_{21}$ and $W_{32}$ are the outer-dependencies that have been evaluated by the FANP method (Figure 9).

$$W = \begin{array}{cc} & \begin{array}{ccc} SC & C & P \end{array} \\ \begin{array}{r} \textit{Severity of Consequence } (SC) \\ \textit{Categories } (C) \\ \textit{Parameters } (P) \end{array} & \begin{bmatrix} 0 & 0 & 0 \\ W_{21} & W_{22} & 0 \\ 0 & W_{32} & W_{33} \end{bmatrix} \end{array}$$

**Figure 7. Severity of consequence supermatrix.**

$$W_{22} = \begin{array}{cc} & \begin{array}{ccc} C_1 & C_2 & C_3 \end{array} \\ \begin{array}{c} C_1 \\ C_2 \\ C_3 \end{array} & \begin{bmatrix} 0.26 & 0.31 & 0.19 \\ 0.8 & 0.25 & 0.23 \\ 0.94 & 0.73 & 0.19 \end{bmatrix} \end{array}$$

**Inner dependencies among categories.**

$$W_{33} = \begin{array}{cc} & \begin{array}{ccccccccccccccccccc} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} & C_{17} & C_{18} & C_{19} & C_{110} & C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} & C_{31} & C_{32} & C_{33} \end{array} \\ \begin{array}{c} C_{11} \\ C_{12} \\ C_{13} \\ C_{14} \\ C_{15} \\ C_{16} \\ C_{17} \\ C_{18} \\ C_{19} \\ C_{110} \\ C_{21} \\ C_{22} \\ C_{23} \\ C_{24} \\ C_{25} \\ C_{26} \\ C_{31} \\ C_{32} \\ C_{33} \\ C_{34} \end{array} & \begin{bmatrix}
0.13 & 0.21 & 0.2 & 0.2 & 0.16 & 0.2 & 0.17 & 0.17 & 0.17 & 0.15 & 0.14 & 0.13 & 0.11 & 0.14 & 0.18 & 0.05 & 0.13 & 0.07 & 0.14 \\
0.2 & 0.17 & 0.19 & 0.22 & 0.2 & 0.22 & 0.2 & 0.19 & 0.19 & 0.19 & 0.19 & 0.11 & 0.12 & 0.16 & 0.19 & 0.05 & 0.14 & 0.1 & 0.16 \\
0.21 & 0.23 & 0.16 & 0.23 & 0.21 & 0.24 & 0.2 & 0.2 & 0.21 & 0.19 & 0.21 & 0.12 & 0.13 & 0.19 & 0.21 & 0.06 & 0.18 & 0.1 & 0.17 \\
0.19 & 0.22 & 0.2 & 0.16 & 0.19 & 0.22 & 0.21 & 0.2 & 0.2 & 0.2 & 0.23 & 0.12 & 0.14 & 0.19 & 0.2 & 0.07 & 0.15 & 0.11 & 0.21 \\
0.18 & 0.21 & 0.18 & 0.18 & 0.14 & 0.21 & 0.16 & 0.19 & 0.18 & 0.17 & 0.18 & 0.12 & 0.12 & 0.14 & 0.18 & 0.05 & 0.14 & 0.07 & 0.16 \\
0.19 & 0.21 & 0.18 & 0.2 & 0.18 & 0.15 & 0.16 & 0.19 & 0.17 & 0.17 & 0.15 & 0.14 & 0.13 & 0.14 & 0.16 & 0.07 & 0.13 & 0.09 & 0.17 \\
0.17 & 0.19 & 0.17 & 0.17 & 0.15 & 0.19 & 0.12 & 0.18 & 0.17 & 0.18 & 0.17 & 0.09 & 0.1 & 0.12 & 0.14 & 0.04 & 0.13 & 0.07 & 0.14 \\
0.17 & 0.17 & 0.16 & 0.16 & 0.16 & 0.2 & 0.15 & 0.12 & 0.13 & 0.13 & 0.16 & 0.12 & 0.13 & 0.13 & 0.14 & 0.06 & 0.11 & 0.07 & 0.14 \\
0.18 & 0.22 & 0.2 & 0.19 & 0.2 & 0.21 & 0.19 & 0.19 & 0.15 & 0.19 & 0.21 & 0.12 & 0.12 & 0.17 & 0.18 & 0.07 & 0.15 & 0.09 & 0.18 \\
0.16 & 0.2 & 0.18 & 0.17 & 0.19 & 0.2 & 0.2 & 0.2 & 0.19 & 0.14 & 0.21 & 0.12 & 0.12 & 0.16 & 0.17 & 0.05 & 0.16 & 0.08 & 0.17 \\
0.19 & 0.25 & 0.21 & 0.23 & 0.21 & 0.23 & 0.19 & 0.23 & 0.22 & 0.19 & 0.16 & 0.13 & 0.14 & 0.19 & 0.18 & 0.1 & 0.16 & 0.08 & 0.19 \\
0.19 & 0.16 & 0.15 & 0.14 & 0.16 & 0.21 & 0.17 & 0.16 & 0.16 & 0.15 & 0.15 & 0.09 & 0.14 & 0.15 & 0.14 & 0.09 & 0.14 & 0.08 & 0.14 \\
0.22 & 0.26 & 0.23 & 0.23 & 0.23 & 0.24 & 0.21 & 0.23 & 0.22 & 0.22 & 0.23 & 0.16 & 0.12 & 0.17 & 0.17 & 0.11 & 0.17 & 0.09 & 0.18 \\
0.21 & 0.22 & 0.21 & 0.21 & 0.19 & 0.22 & 0.2 & 0.22 & 0.21 & 0.21 & 0.22 & 0.15 & 0.15 & 0.13 & 0.18 & 0.12 & 0.14 & 0.09 & 0.19 \\
0.16 & 0.19 & 0.18 & 0.17 & 0.16 & 0.19 & 0.16 & 0.16 & 0.17 & 0.15 & 0.17 & 0.11 & 0.11 & 0.13 & 0.12 & 0.06 & 0.13 & 0.07 & 0.14 \\
0.12 & 0.12 & 0.1 & 0.11 & 0.1 & 0.14 & 0.1 & 0.13 & 0.1 & 0.08 & 0.08 & 0.1 & 0.11 & 0.1 & 0.09 & 0.03 & 0.06 & 0.04 & 0.1 \\
0.21 & 0.24 & 0.21 & 0.2 & 0.2 & 0.22 & 0.19 & 0.2 & 0.19 & 0.2 & 0.21 & 0.12 & 0.11 & 0.14 & 0.17 & 0.06 & 0.12 & 0.07 & 0.22 \\
0.13 & 0.19 & 0.13 & 0.12 & 0.15 & 0.14 & 0.12 & 0.14 & 0.13 & 0.16 & 0.17 & 0.12 & 0.1 & 0.12 & 0.12 & 0.05 & 0.09 & 0.05 & 0.12 \\
0.21 & 0.25 & 0.22 & 0.23 & 0.21 & 0.23 & 0.2 & 0.2 & 0.2 & 0.22 & 0.22 & 0.15 & 0.12 & 0.17 & 0.17 & 0.06 & 0.16 & 0.1 & 0.15 \\
0.23 & 0.27 & 0.25 & 0.23 & 0.22 & 0.25 & 0.22 & 0.23 & 0.23 & 0.23 & 0.24 & 0.15 & 0.16 & 0.21 & 0.2 & 0.06 & 0.21 & 0.11 & 0.25
\end{bmatrix} \end{array}$$

**b. Inner dependencies among events.**

**Figure 8. Inner dependency matrices evaluated by FDEMATEL.**

$$W_{21} = \begin{bmatrix} 0.43 \\ 0.33 \\ 0.24 \end{bmatrix}$$

**a. Outer dependencies of categories.**

$$W_{32} = \begin{bmatrix}
0.12 & 0 & 0 \\
0.12 & 0 & 0 \\
0.08 & 0 & 0 \\
0.09 & 0 & 0 \\
0.08 & 0 & 0 \\
0.12 & 0 & 0 \\
0.09 & 0 & 0 \\
0.11 & 0 & 0 \\
0.1 & 0 & 0 \\
0.09 & 0 & 0 \\
0 & 0.18 & 0 \\
0 & 0.18 & 0 \\
0 & 0.18 & 0 \\
0 & 0.16 & 0 \\
0 & 0.17 & 0 \\
0 & 0.13 & 0 \\
0 & 0 & 0.26 \\
0 & 0 & 0.24 \\
0 & 0 & 0.24 \\
0 & 0 & 0.27
\end{bmatrix}$$

**b. Outer dependencies of events.**

**Figure 9. Outer dependency matrices evaluating FANP.**

**Table 11. Ranking severity of main flyrock intermediate events consequence.**

| Consequence (%) | Consequence level | Rating |
|---|---|---|
| ≥ 55.1 | Very large | 5 |
| 40.6 – 55.1 | Large | 4 |
| 26.1 – 40.6 | Medium | 3 |
| 11.57 -26.1 | Low | 2 |
| ≤ 11.57 | Very low | 1 |

**Table 12. Severity of the main flyrock intermediate event consequence.**

| Symbol | Name | Severity of consequence | Rate |
|---|---|---|---|
| $TE_1$ | Design error | 49 | 4 |
| $TE_2$ | Human error | 29 | 3 |
| $TE_3$ | Natural influence | 21 | 2 |

| | flyrock | $C_1$ | $C_2$ | $C_3$ | $C_{11}$ | $C_{12}$ | $C_{13}$ | $C_{14}$ | $C_{15}$ | $C_{16}$ | $C_{17}$ | $C_{18}$ | $C_{19}$ | $C_{110}$ | $C_{21}$ | $C_{22}$ | $C_{23}$ | $C_{24}$ | $C_{25}$ | $C_{26}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ | $C_{34}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *flyrock* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_1$ | 0.43 | 0.26 | 0.31 | 0.19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_2$ | 0.33 | 0.8 | 0.25 | 0.23 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_3$ | 0.24 | 0.94 | 0.73 | 0.19 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_{11}$ | 0 | 0.12 | 0 | 0 | 0.13 | 0.21 | 0.2 | 0.2 | 0.16 | 0.2 | 0.17 | 0.17 | 0.17 | 0.15 | 0.14 | 0.13 | 0.11 | 0.14 | 0.18 | 0.05 | 0.13 | 0.07 | 0.14 | 0.15 |
| $C_{12}$ | 0 | 0.12 | 0 | 0 | 0.2 | 0.17 | 0.19 | 0.22 | 0.2 | 0.22 | 0.2 | 0.19 | 0.19 | 0.19 | 0.19 | 0.11 | 0.12 | 0.16 | 0.19 | 0.05 | 0.14 | 0.1 | 0.16 | 0.16 |
| $C_{13}$ | 0 | 0.08 | 0 | 0 | 0.21 | 0.23 | 0.16 | 0.23 | 0.21 | 0.24 | 0.2 | 0.2 | 0.21 | 0.19 | 0.21 | 0.12 | 0.13 | 0.19 | 0.21 | 0.06 | 0.18 | 0.1 | 0.17 | 0.17 |
| $C_{14}$ | 0 | 0.09 | 0 | 0 | 0.19 | 0.22 | 0.2 | 0.16 | 0.19 | 0.22 | 0.21 | 0.2 | 0.2 | 0.2 | 0.23 | 0.12 | 0.14 | 0.19 | 0.2 | 0.07 | 0.15 | 0.11 | 0.21 | 0.17 |
| $C_{15}$ | 0 | 0.08 | 0 | 0 | 0.18 | 0.21 | 0.18 | 0.18 | 0.14 | 0.21 | 0.16 | 0.19 | 0.18 | 0.17 | 0.18 | 0.12 | 0.12 | 0.14 | 0.18 | 0.05 | 0.14 | 0.07 | 0.16 | 0.15 |
| $C_{16}$ | 0 | 0.12 | 0 | 0 | 0.19 | 0.21 | 0.18 | 0.2 | 0.18 | 0.15 | 0.16 | 0.19 | 0.17 | 0.17 | 0.15 | 0.14 | 0.13 | 0.14 | 0.16 | 0.07 | 0.13 | 0.09 | 0.17 | 0.16 |
| $C_{17}$ | 0 | 0.09 | 0 | 0 | 0.17 | 0.19 | 0.17 | 0.17 | 0.15 | 0.19 | 0.12 | 0.18 | 0.17 | 0.18 | 0.17 | 0.09 | 0.1 | 0.12 | 0.14 | 0.04 | 0.13 | 0.07 | 0.14 | 0.13 |
| $C_{18}$ | 0 | 0.11 | 0 | 0 | 0.17 | 0.17 | 0.16 | 0.16 | 0.16 | 0.2 | 0.15 | 0.12 | 0.13 | 0.13 | 0.16 | 0.12 | 0.13 | 0.13 | 0.14 | 0.06 | 0.11 | 0.07 | 0.14 | 0.15 |
| $C_{19}$ | 0 | 0.1 | 0 | 0 | 0.18 | 0.22 | 0.2 | 0.19 | 0.2 | 0.21 | 0.19 | 0.19 | 0.15 | 0.19 | 0.21 | 0.12 | 0.12 | 0.17 | 0.18 | 0.07 | 0.15 | 0.09 | 0.18 | 0.15 |
| $C_{110}$ | 0 | 0.09 | 0 | 0 | 0.16 | 0.2 | 0.18 | 0.17 | 0.19 | 0.2 | 0.2 | 0.2 | 0.19 | 0.14 | 0.21 | 0.12 | 0.12 | 0.16 | 0.17 | 0.05 | 0.16 | 0.08 | 0.17 | 0.15 |
| $C_{21}$ | 0 | 0 | 0.18 | 0 | 0.19 | 0.25 | 0.21 | 0.23 | 0.21 | 0.23 | 0.19 | 0.23 | 0.22 | 0.19 | 0.16 | 0.13 | 0.14 | 0.19 | 0.18 | 0.1 | 0.16 | 0.08 | 0.19 | 0.18 |
| $C_{22}$ | 0 | 0 | 0.18 | 0 | 0.19 | 0.16 | 0.15 | 0.14 | 0.16 | 0.21 | 0.17 | 0.16 | 0.16 | 0.15 | 0.15 | 0.09 | 0.14 | 0.15 | 0.14 | 0.09 | 0.14 | 0.08 | 0.14 | 0.14 |
| $C_{23}$ | 0 | 0 | 0.18 | 0 | 0.22 | 0.26 | 0.23 | 0.23 | 0.23 | 0.24 | 0.21 | 0.23 | 0.22 | 0.22 | 0.23 | 0.16 | 0.12 | 0.17 | 0.17 | 0.11 | 0.17 | 0.09 | 0.18 | 0.18 |
| $C_{24}$ | 0 | 0 | 0.16 | 0 | 0.21 | 0.22 | 0.21 | 0.21 | 0.19 | 0.22 | 0.2 | 0.22 | 0.21 | 0.21 | 0.22 | 0.15 | 0.15 | 0.13 | 0.18 | 0.12 | 0.14 | 0.09 | 0.19 | 0.17 |
| $C_{25}$ | 0 | 0 | 0.17 | 0 | 0.16 | 0.19 | 0.18 | 0.17 | 0.16 | 0.19 | 0.16 | 0.16 | 0.17 | 0.15 | 0.17 | 0.11 | 0.11 | 0.13 | 0.12 | 0.06 | 0.13 | 0.07 | 0.14 | 0.15 |
| $C_{26}$ | 0 | 0 | 0.13 | 0 | 0.12 | 0.12 | 0.1 | 0.11 | 0.1 | 0.14 | 0.1 | 0.13 | 0.1 | 0.08 | 0.08 | 0.1 | 0.11 | 0.1 | 0.09 | 0.03 | 0.06 | 0.04 | 0.1 | 0.07 |
| $C_{31}$ | 0 | 0 | 0 | 0.26 | 0.21 | 0.24 | 0.21 | 0.2 | 0.2 | 0.22 | 0.19 | 0.2 | 0.19 | 0.2 | 0.21 | 0.12 | 0.11 | 0.14 | 0.17 | 0.06 | 0.12 | 0.07 | 0.22 | 0.21 |
| $C_{32}$ | 0 | 0 | 0 | 0.24 | 0.13 | 0.19 | 0.13 | 0.12 | 0.15 | 0.14 | 0.12 | 0.14 | 0.13 | 0.16 | 0.17 | 0.12 | 0.1 | 0.12 | 0.12 | 0.05 | 0.09 | 0.05 | 0.12 | 0.13 |
| $C_{33}$ | 0 | 0 | 0 | 0.24 | 0.21 | 0.25 | 0.22 | 0.23 | 0.21 | 0.23 | 0.2 | 0.2 | 0.2 | 0.22 | 0.22 | 0.15 | 0.12 | 0.17 | 0.17 | 0.06 | 0.16 | 0.1 | 0.15 | 0.21 |
| $C_{34}$ | 0 | 0 | 0 | 0.27 | 0.23 | 0.27 | 0.25 | 0.23 | 0.22 | 0.25 | 0.22 | 0.23 | 0.23 | 0.23 | 0.24 | 0.15 | 0.16 | 0.21 | 0.2 | 0.06 | 0.21 | 0.11 | 0.25 | 0.16 |

**a.Unweighted supermatrix.**

| | flyrock | $C_1$ | $C_2$ | $C_3$ | $C_{11}$ | $C_{12}$ | $C_{13}$ | $C_{14}$ | $C_{15}$ | $C_{16}$ | $C_{17}$ | $C_{18}$ | $C_{19}$ | $C_{110}$ | $C_{21}$ | $C_{22}$ | $C_{23}$ | $C_{24}$ | $C_{25}$ | $C_{26}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ | $C_{34}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *flyrock* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_1$ | 0.43 | 0.09 | 0.13 | 0.12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_2$ | 0.33 | 0.27 | 0.11 | 0.14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_3$ | 0.24 | 0.31 | 0.32 | 0.12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_{11}$ | 0 | 0.04 | 0 | 0 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.05 | 0.04 | 0.04 | 0.05 |
| $C_{12}$ | 0 | 0.04 | 0 | 0 | 0.05 | 0.04 | 0.05 | 0.06 | 0.05 | 0.05 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.06 | 0.04 | 0.05 | 0.06 | 0.05 | 0.05 |
| $C_{13}$ | 0 | 0.03 | 0 | 0 | 0.06 | 0.05 | 0.04 | 0.06 | 0.06 | 0.06 | 0.06 | 0.05 | 0.06 | 0.05 | 0.06 | 0.05 | 0.05 | 0.06 | 0.06 | 0.04 | 0.06 | 0.06 | 0.05 | 0.05 |
| $C_{14}$ | 0 | 0.03 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.04 | 0.05 | 0.05 | 0.06 | 0.05 | 0.06 | 0.06 | 0.06 | 0.05 | 0.06 | 0.06 | 0.06 | 0.06 | 0.05 | 0.07 | 0.06 | 0.05 |
| $C_{15}$ | 0 | 0.03 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.05 | 0.04 | 0.05 | 0.05 |
| $C_{16}$ | 0 | 0.04 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $C_{17}$ | 0 | 0.03 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.05 | 0.03 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 | 0.03 | 0.05 | 0.04 | 0.04 | 0.04 |
| $C_{18}$ | 0 | 0.04 | 0 | 0 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.04 | 0.03 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.04 | 0.04 | 0.05 | 0.04 | 0.05 | 0.04 | 0.05 |
| $C_{19}$ | 0 | 0.03 | 0 | 0 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.05 | 0.06 | 0.05 | 0.05 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $C_{110}$ | 0 | 0.03 | 0 | 0 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.06 | 0.05 | 0.05 | 0.04 | 0.06 | 0.05 | 0.05 | 0.05 | 0.05 | 0.04 | 0.06 | 0.05 | 0.05 | 0.05 |
| $C_{21}$ | 0 | 0 | 0.08 | 0 | 0.05 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.05 | 0.06 | 0.06 | 0.05 | 0.04 | 0.05 | 0.06 | 0.06 | 0.06 | 0.07 | 0.06 | 0.05 | 0.06 | 0.06 |
| $C_{22}$ | 0 | 0 | 0.08 | 0 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.06 | 0.05 | 0.04 | 0.07 | 0.05 | 0.05 | 0.04 | 0.04 |
| $C_{23}$ | 0 | 0 | 0.08 | 0 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.07 | 0.05 | 0.06 | 0.05 | 0.08 | 0.06 | 0.06 | 0.05 | 0.06 |
| $C_{24}$ | 0 | 0 | 0.07 | 0 | 0.06 | 0.05 | 0.06 | 0.06 | 0.05 | 0.05 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.04 | 0.05 | 0.09 | 0.05 | 0.05 | 0.06 | 0.06 |
| $C_{25}$ | 0 | 0 | 0.07 | 0 | 0.04 | 0.05 | 0.05 | 0.05 | 0.04 | 0.05 | 0.05 | 0.04 | 0.05 | 0.04 | 0.05 | 0.04 | 0.04 | 0.04 | 0.03 | 0.05 | 0.04 | 0.04 | 0.04 | 0.05 |
| $C_{26}$ | 0 | 0 | 0.05 | 0 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.03 | 0.02 | 0.02 | 0.04 | 0.04 | 0.03 | 0.03 | 0.02 | 0.02 | 0.02 | 0.03 | 0.02 |
| $C_{31}$ | 0 | 0 | 0 | 0.16 | 0.06 | 0.06 | 0.06 | 0.05 | 0.06 | 0.05 | 0.06 | 0.05 | 0.05 | 0.06 | 0.06 | 0.05 | 0.04 | 0.05 | 0.05 | 0.05 | 0.04 | 0.04 | 0.07 | 0.07 |
| $C_{32}$ | 0 | 0 | 0 | 0.15 | 0.04 | 0.05 | 0.04 | 0.03 | 0.04 | 0.03 | 0.03 | 0.04 | 0.04 | 0.05 | 0.05 | 0.05 | 0.04 | 0.04 | 0.04 | 0.04 | 0.03 | 0.03 | 0.04 | 0.04 |
| $C_{33}$ | 0 | 0 | 0 | 0.15 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.05 | 0.06 | 0.06 | 0.06 | 0.06 | 0.05 | 0.06 | 0.05 | 0.04 | 0.06 | 0.06 | 0.04 | 0.07 |
| $C_{34}$ | 0 | 0 | 0 | 0.16 | 0.06 | 0.06 | 0.07 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.07 | 0.06 | 0.05 | 0.08 | 0.07 | 0.08 | 0.05 |

**b.Weighted supermatrix.**

| | flyrock | $C_1$ | $C_2$ | $C_3$ | $C_{11}$ | $C_{12}$ | $C_{13}$ | $C_{14}$ | $C_{15}$ | $C_{16}$ | $C_{17}$ | $C_{18}$ | $C_{19}$ | $C_{110}$ | $C_{21}$ | $C_{22}$ | $C_{23}$ | $C_{24}$ | $C_{25}$ | $C_{26}$ | $C_{31}$ | $C_{32}$ | $C_{33}$ | $C_{34}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *flyrock* | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_1$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_2$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_3$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_{11}$ | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $C_{12}$ | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $C_{13}$ | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| $C_{14}$ | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| $C_{15}$ | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $C_{16}$ | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $C_{17}$ | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| $C_{18}$ | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| $C_{19}$ | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $C_{110}$ | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $C_{21}$ | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| $C_{22}$ | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $C_{23}$ | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| $C_{24}$ | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| $C_{25}$ | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| $C_{26}$ | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| $C_{31}$ | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| $C_{32}$ | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| $C_{33}$ | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |
| $C_{34}$ | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 |

**c. Limited supermatrix.**

**Figure 10. Procedure of weight calculation using supermatrix.**

## 2.4. Determining number of risk

In order to finally assess the risk of flyrock in surface mines, after determining the probability and severity of the consequences of each one of the terminal events and the risk of flyrock in mines, it is necessary to calculate their risk number. As mentioned in the previous sections, the number of risk events is obtained by multiplying the probability and severity of the consequence. The quantitative numbers of the probability of occurrence and the severity of the consequence of each one of the main flyrock intermediate events are indicated in Table 13. Also the risk matrix of each one of the terminal events is displayed in Figure 11. As it can be seen, in the risk matrix, the design error, human error, and natural influences were considered, respectively, as the undesirable events, tolerable events, and ignorable events.

**Table 13. Flyrock risk number.**

| Symbol | Probability of occurrence | Severity of consequence | Risk number | Risk class |
|---|---|---|---|---|
| $IE_1$ | 3 | 4 | 12 | Undesirable |
| $IE_2$ | 2 | 3 | 6 | Tolerable |
| $IE_3$ | 1 | 2 | 2 | Ignorable |

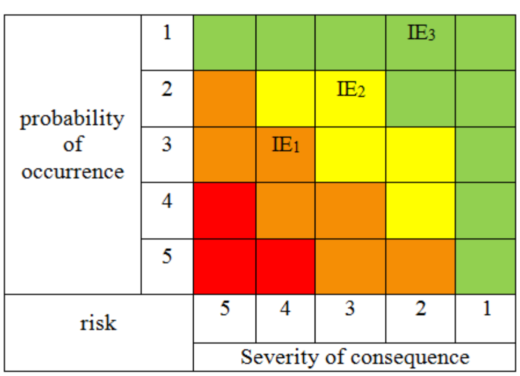


**Figure 11. Risk matrix of fly rock in surface mines.**

## 4. Discussion

Based on the results s the operation by the head of the mine;

1. Detailed study of the geological surveys by a number of experienced professionals

## 4. Conclusions

In the present work, a general approach was developed for risk assessment of flyrock in surface mines using the FFTA-MCDM combination. For this purpose, the causing events of flyrock in surface mines were identified, and these events were divided into three major groups including the design error, human error, and natural error. FFTA was used to calculate the probabilities of events and flyrock occurrence; the design error had the most occurrence probability between the events. Then combining DEMATEL and FANP was used to propose the flyrock consequence severities; the design error had the most consequence severities between the events. Finally, using the obtained probabilities and severities for the design error, human error, and natural influence events, the risk matrix was constructed. Based on the risk matrix, the risk number of flyrock occurrence due to the design errors, human errors, and natural influence were 12, 6, and 2, respectively. The flyrock risk assessment performed in this work is a useful scientific and systematic approach for analyzing many events that have contribution in flyrock occurrences. Field experiences and observations show that the actual state of surface mines is in accordance with this approach. Therefore, it can be concluded that the approach used is of high validity for risk assessment of flyrock in the surface mines. As, in this work, the OR gates were used for connection of the basic events to the intermediate and top events, it is suggested that in the future research works, by more investigation about the flyrock causing events, the AND gates are used for these connections.

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# ارزیابی ریسک پرتاب سنگ در معدنکاری سطحی با استفاده از ترکیب روش تحلیل درخت خطا و تصمیم‌گیری چند معیاره

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**چکیده:**

روش چالزنی و آتشکاری به‌دلیل انعطاف‌پذیری بالا در برابر تغییرات و هزینه‌های سرمایه‌گذاری انتخاب اول برای خردایش سنگ در معادن سطحی و زیرزمینی است. با این وجود هر روشی معایب و مزایای خاص خود را دارد. یکی از معایب روش چالزنی و آتشکاری پدیده پرتاب سنگ است، همواره مهندسین معدن در اجرای عملیات آتشکاری در معادن سطحی با آن مواجه می‌شوند. پرتاب سنگ موجب تخریب تجهیزات سطحی و ساختارها و مرگ ومیر کارکنان خواهد شد از این رو ارزیابی ریسک امری ضروری است. برای ارزیابی ریسک پرتاب سنگ، باید شدت پیامد و احتمال وقوع رویدادها شناسایی شوند. برای این منظور، از ترکیب روش تحلیل درخت خطا و تصمیم‌گیری چند معیاره استفاده شد. بر اساس نتایج بدست آمده، ارتباط بین رویدادهای پرتاب سنگ در معادن سطحی به سه بخش اصلی خطای طراحی، انسانی و طبیعی تقسیم‌بندی شد. در نهایت با استفاده از احتمال وقوع و شدت پیامد برای این سه گروه، ماتریس ریسک ایجاد شد. بر اساس ماتریس ریسک اعداد ریسک رویدادهای پرتاب سنگ در نتیجه خطاهای طراحی، انسانی و اثرات طبیعی به ترتیب ۱۲، ۶ و ۲ محاسبه شد. از این رو به منظور کاهش ریسک پرتاب سنگ، انتخاب مقدار مناسب پارامترهای الگوی آتشکاری مانند، بارسنگ، فاصله‌داری، تاخیرهای انفجار و قطر چال برای مهندسین امری ضروری است.

**کلمات کلیدی:** ارزیابی ریسک، FFTA، پرتاب سنگ، معدنکاری سطحی، MCDM.