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A risk analysis model for mining accidents using a fuzzy approach based on fault tree analysis

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Abstract

Purpose – Risk analysis is a critical investigation field for many sector and organization to maintain the information management reliable. Since the mining is one of the riskiest sectors for both workers and management, comprehensive risk analysis should be carried out. By developing a risk analysis methodology, to explore the undesired events with their main reasons comprehensively that may occur during a particular process and perform risk analysis for these events are aimed in this study. For performing risk analysis, discovering and defining the potential accidents and incident including their root causes are important contributions to the study as distinct from the related literature. The fuzzy approach is used substantially to obtain the important inferences about the hazardous process by identifying the critical risk points in the processes. In the scope of the study, the proposed methodology is applied to an underground chrome mine and obtaining significant findings of mining risky operations is targeted.
Design/methodology/approach – Fault tree analysis and fuzzy approach are used for performing the risk analysis. When determining the probability and the consequences of the events which are essential components for the risk analysis, expressions of the heterogeneous expert group are considered by means of the linguistic terms. Fault tree analysis and fuzzy approach present a quiet convenience solution together to specify the possible accidents and incidents in the particular process and determine the values for the basis risk components.
Findings – This study primarily presents a methodology for a comprehensive risk analysis. By implementing the proposed methodology to the underground loading and conveying processes of a chrome mine, 28 different undesired events that may occur during the processes are specified. With the performing risk analysis for these events, it is established that the employee's physical constraint while working with the shovel in the fore area, the falling of materials on employees from the chute and the scaling bar injuries are found out as the riskiest undesired events in the underground loading and conveying process of the mine.
Practical implications – The proposed methodology provides a confidential and comprehensive method for risk analysis of the undesired events in a particular process. The capability of fault tree analysis for specifying the undesired events systematically and the applicability of fuzzy approach for converting the experts' linguistic expressions to the mathematical values, provide a significant advantage and convenience for the risk analysis.
Originality/value – The major contribution of this paper is to develop a methodology for the risk analysis of a variety of mining accidents and incidents. The proposed methodology can be applied to many production processes to investigate the dangerous operations comprehensively and find out the efficient management strategies. Before performing the risk analysis, determining the all possible accidents and incidents in the particular process using the fault tree analysis provide the effectiveness and the originality of the study. Also using the fuzzy logic to find out the consequences of the events with experts' linguistic expressions, provides an efficient method for performing risk analysis.

Keywords Risk analysis, Fault tree analysis, Fuzzy logic, Chrome mining.
Paper type Research paper

1. Introduction

Upon evaluation of the long-term accident statistics, it is inferred that the mining sector carries the risk of accidents above average when compared to the other sectors (Azapagic, 2004). Because, mining sector includes many high-risk activities, revealing that some features such as environmental conditions with a significant presence of humidity, dust or falling rocks have an important influence on the number and severity of accidents or incidents (Sanmiquel *et al*., 2015). Maintaining of the mining processes uninterruptedly and safely is an important issue. For an acceptable level of risk in mines, it is crucial to specify all the accidents and incidents comprehensively and observe the causes of the undesired events carefully. In this way, the priority fields might be specified and the improvement plans might be constituted to minimize the risk in mines. One of the systematic methods for analyzing the cause of risks is the fault tree analysis with graphic expression by adopting a deductive method, in which a specific risk that is only qualitatively recognized from a proper primary system (Hyun *et al*., 2015).

The main purpose of this study is to identify the accidents and incidents with their root causes in a mine and to perform a risk analysis of these undesired events. For the risk analysis, a detailed methodology which is proper for the purpose of the study is developed using fault tree analysis and fuzzy approach. The methodology also enables to use the expert judgments without historical data for the analysis. It has been successfully applied to underground loading and conveying processes of a chrome mine within the scope of the research. Chrome being an important natural component is situated in metal mines, and it is a solid raw material used in the industrial sectors. Even though chrome mining is less risky than coal mining, harsh and dangerous working conditions of underground mining obstruct the maintenance of the mine extraction processes continuously and safely. Regardless of the type of mine, mining accidents and incidents may occur very often especially during many activities carried out by labour-intensive processes.

Many accidents and incidents that may occur are specified comprehensively by implementing the proposed methodology to the particular processes of a mine Then occurrence probabilities of the accidents and incidents are determined through the quantitative side of the analysis, and consequences of the events are assigned. After getting the values for main components of the risk analysis, risk evaluation for the all possible accidents and incidents is performed. Because of the insufficient statistical data for probabilities and consequences of the events, fuzzy approach that ensures to infer the needed information from the experts' judgments is used. Fuzzy approach allows to use the experts' linguistic expressions instead of statistical data for the analysis and reduces the uncertainties about the data.

After the literature review about the concepts and methods in the study are given in Section 2, all the details about the proposed risk analysis methodology are presented in Section 3. The implementation of the methodology to the particular processes of an underground mine is stated in Section 4 while the conclusions of the study together with the recommendations are provided in Section 5.

The highlights of the proposed methodology can be given as 1) specifying the possible accidents and incidents that may occur in a particular process using the effective method of the fault tree analysis, 2) consulting with the various experts to provide the accuracy of the study, 3) determining of the undesired events' probabilities which are needed for risk analysis utilizing the root causes established using fault tree analysis, and 4) converting the experts' qualitative expressions about both probabilities and the consequences of the events to the numerical values using the fuzzy approach

2. Literature review

There is a crucial relationship between the hazards, risks and the accidents. The risk is the effect of uncertainty on objectives caused by variability and specific uncertain events, and it is often measured concerning consequences and likelihood. Hazards are the prerequisites for risks, and when all the hazards are safely controlled, there is no risk for unwanted events (Liu et al., 2015). The focus of risk analysis concentrates on evaluating the undesired events that have hazardous conditions by considering their occurrence probabilities and possible consequences. In this way, it might be possible to manage them by constituting the control measures and prevent or mitigate the risk situations. And because of the limited resources for managing the risk in an organization, it is crucial to find out the underlying events regarding its occurrence frequency and possible consequences.

In literature, there are a lot of studies analyzing the mining accidents to specify the preventing policies for decreasing the risk in mines. Studies can be categorized under the different titles as investigating the causes of a distinct type of mining accident (Jiang *et al*., 2012; Sarı *et al*., 2004), analyzing the accidents based on countries (Sanmiquel *et al*., 2015; Sen *et al*., 2015; Wu *et al*., 2011; Michelo *et al*., 2009; Komljenovic *et al*., 2008; Sarı *et al*., 2004), investigating the accidents or failures related equipment (Sen *et al*., 2015; Zhang *et al*., 2014; Bellamy and Pravica, 2011; Groves *et al*., 2007) or statistical accident analysis (Spada and Burgherr, 2016; Sanmiquel *et al*., 2015; Groves *et al*., 2007).

The risky situations of a mine vary across mine types, the used methods for extraction and the geological structure of the mine located region. Therefore, a methodology which is applicable for every type of mine is proposed by using the fault tree analysis. The fault tree analysis is a descriptive and relational research method. The purpose of creating a fault tree is to find out the causes of an accident or a failure in a system. Fault tree analysis has been used as a popular and an efficient safety analysis tool in variety field in literature. As example, liquid storage tank failure (Yazdi et al, 2017), infectious medical waste management (Makajic-Nikolic et al., 2016), analyzing the high-speed railway accidents (Liu *et al*., 2015), contamination of chemical cargo in marine transportation (Senol *et al*., 2015), diagnosis the failures of coal scraper conveyor (Sen *et al*., 2015), fall risk evaluation of steel construction projects (Leu and Chang, 2015), fire and explosion acidents for steel oil storage tanks (Shi et al., 2014), safety assessment of nuclear power plant (Purba, 2014), fire and explosion of crude oil tanks (Wang et al., 2013), reliability analysis of ventilation system in mining (Meng, 2013), supply failure of drinking water systems (Lindhe *et al*., 2009) and, the transmission of oil and gas in pipelines (Yuhua and Datao, 2005) can be given. In this study, the fault tree analysis is used to find out the possible accidents and incidents with their root causes and to provide a basis for risk analysis of the possible undesired events under a particular process of a mine.

The construction of a fault tree proceeds in a top-down manner, and the undesired events are proceeds to their causes until the root causes are obtained (Leu and Chang, 2015). The fault tree analysis provides for determining the undesired events with their root causes together with their probabilities. The probability of the events can be determined either by subjective or objective means. While subjective methods use judgment, objective methods utilize statistical analysis of the historical data. In practical applications, it is usually difficult or sometimes impossible to find sufficient data for objective probability assessment. In such cases, subjective assessment of probabilities can be used effectively (Duzgun and Einstein, 2004). Therefore, in this study, after specifying the possible accidents and incidents in the mine, expert judgments are used to evaluate the probabilities and the consequences of the specified undesired events. To be converted the expert's qualitative expressions into the numerical values, fuzzy approach presents an effective solution. Lavasani et al. (2015), Sen et al. (2015), (Purba, 2014) and Wang et al. (2013) can be given as example studies which took advantage of the fuzzy approach together using the fault tree analysis. In addition to using the fuzzy approach within the fault tree analysis, we also used it for specifying the consequences of the events for risk analysis. Fault tree analysis together with the fuzzy approach presents a private and practical method which is convenient to the aim of our study.

3. Methodology

In underground mines, there are a considerable number of hazards which include specialized equipment, humidity, rock stresses, dust, and harmful gasses. These hazards have the potential to trigger accidents that can lead to injuries, multi fatalities and/or major asset losses unless risk control measures are implemented that effectively manage them (Liu et al., 2016). To be performed a risk analysis by specifying the risky situations that vary across mine types, the variety of geological, managerial and technical infrastructures, a methodology is developed within the scope of the study. And when it is considered the high risk of the mining activities, such kind of approach and methodology which able to reveal the all possible accidents and incidents in a mine, is inevitably necessary to generate the right risk mitigation strategies.

Risk assessments methodologies incorporates the deterministic (qualitative, quantitative and hybrid) and the stochastic (classic statistical and forecasting modeling) approaches (Marhavilas et al., 2014). In quantitative techniques, the risk can be estimated and expressed by a mathematical equation under the help of real accidents' data recorded on a work site, while qualitative techniques are based mainly on analytical estimation processes and safety-managers' ability; a hybrid technique mixes in a single framework both a qualitative and quantitative method (Marhavilas et al., 2014). The proposed methodology for this study is also a hybrid technique which include both the qualitative and quantitative method since it incorporates the fault tree analysis and fuzzy approach. The stages of the methodology are as following: The first stage is the most important part includes creating the fault tree and specifying the undesired events with their minimal cut sets. The second stage is determining the risk component values of the undesired events as the probability and consequences values. And the last step is performing the risk analysis and drawing the inferences. The structure of the methodology is given in Figure 1.

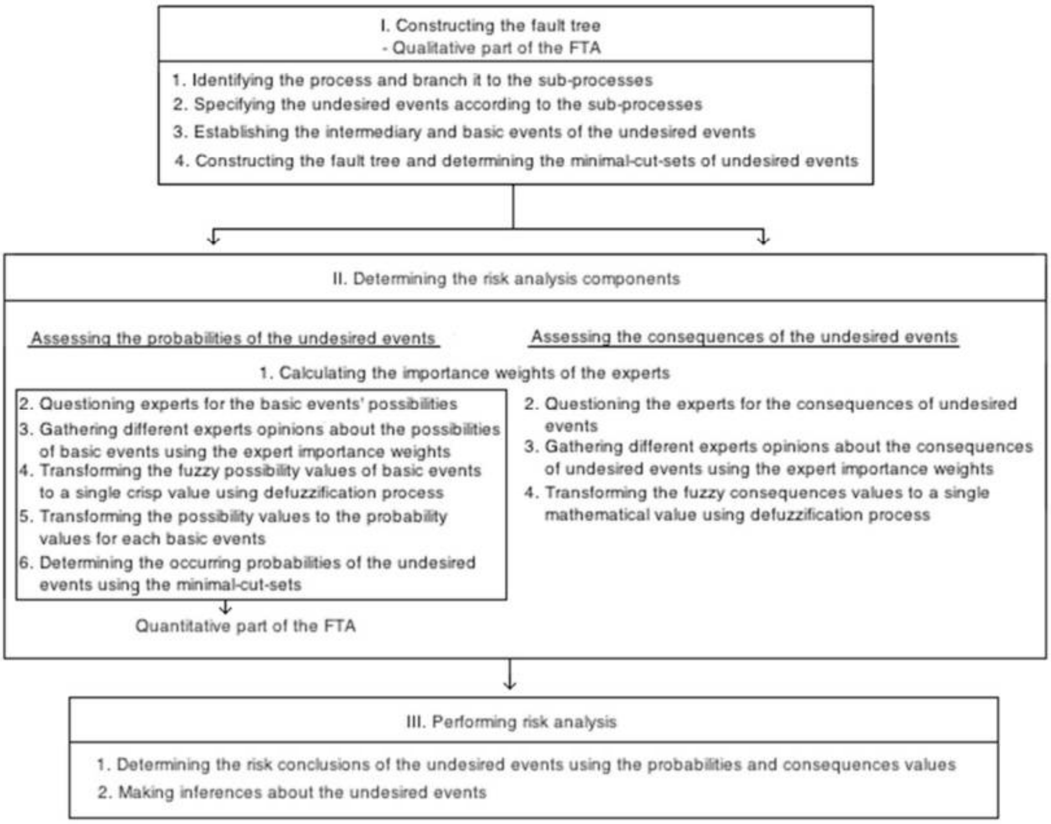

Figure 1: Structure of proposed methodology

After investigation of the mine limited historical accidents and interviews with the experts, it is revealed that the most severe and frequent accidents and incidents in the underground chrome mine have occurred during underground loading and shipment activities. Therefore, the investigation of the loading and conveying activities of the underground mine in detailed and discussing the possible accidents and incidents that have the potential to happen are handled in the study. To discover variety of accidents and incidents with their root causes, fault tree analysis that provides to investigate the hazards in a systematic and illustrative way is used. The studies combined with the fault tree analyses consider a failure or an accident as the top event. In some studies, top event is considered by branching according to the subsystems' failures (Makajic-Nikolic et al., 2016; Lavasani et al., 2015; Sen et al., 2015), in some studies it is considered by separating the accidents or failures according to the types (Yazdi et al., 2017; Hyun et al., 2015; Yuhua and Datao, 2005) and in some studies the top event represents a type of accident directly and without separating the subsystems or types of the failures (Ai et al., 2015; Senol et al., 2015, Zhang et al., 2014; Hauptmanns, 2004). In this study, since the aim is the investigating the variety of possible accidents and incidents, as well and top event is considered as "mine accident" by branching it to subprocesses in the fault tree. The methodology is structured as following:

3.1. Creating the fault tree and specifying the undesired events with their minimal cut sets.

Fault tree analysis is defined as a structured process that identifies potential causes of system failure (Lindhe et al., 2009). In this study, there are two aims of using of the fault tree analysis. First is to reveal the possible accidents and incidents with their root causes in mining processes in a systematic way, qualitatively. Second is to determine the probabilities of the accidents and incidents, quantitatively. By consulting with the experts, the fault tree has structured in a top-down manner comprehensively. In a fault tree, accidents are configured top to bottom in the tree, in a way which shows intermediary and basic events in their occurrence. In the study, the sub-processes in the underground loading and conveying processes are qualified as intermediary events. The undesired events that are under these intermediary events together with their root causes are included to the tree appropriately for the structure of the fault tree.

When constructing a fault tree, the relationships between events are represented by means of gates, of which AND-gates and OR-gates are the most widely used (Khakzad et al., 2011). The "AND" gate refers to the event that might happen in case of occurrence of all events it includes while the "OR" gate refers to the event that might happen in the event of occurrence of any of the events it includes. Top and intermediary events are indicated by a rectangle, and the root causes for events' occurrence are stated as "basic event" (Figure 2).

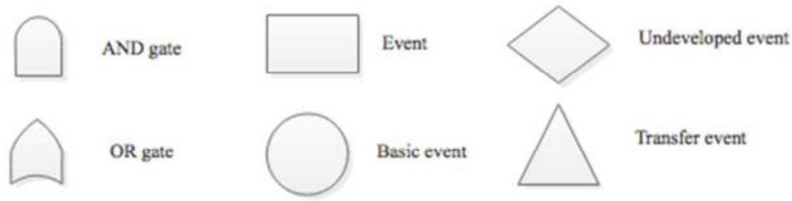

Figure 2: Basic symbols used in the fault tree analysis

After constructing the fault tree that presents the all event series, within the qualitative side of the fault tree analysis, minimal cut sets (MCS) of the undesired events need to be specified. A minimal cut set presents the necessary conditions with the minimum number of events to occur an undesired event. Minimal cut sets can be first order, second order, third order and so on according to the number of having events within the set. Generally speaking, the less the order of MCS is, the higher is its occurrence frequency. Therefore, the first-order MCS and basic events with high occurrence frequency would be considered in advance in FTA (Yuhua and Datao, 2005). After specifying the undesired events using the fault tree, the minimal cut sets are defined for each undesired event. Thus, the study is prepared for the quantitative analysis.

3.2. Determining the probabilities of the undesired events.

Fault tree analysis serves estimation about occurrence probability of a top event using generic data. In our study, we are interested in evaluating the probabilities of specified undesired events reveal within the fault tree rather than the probability of the top event. To be determined the probabilities of the specified accidents and incidents, the probabilities of basic events should be determined firstly, since they emanate from the basic events and intermediary events. The fuzzy approach is used to identify the probabilities of the the basic events, contrarily conventional fault tree analysis that considers the occurrence probabilities of the basic events as exact values. Because, it is often difficult to estimate precise occurrence probabilities of the basic events, even if they may have never failed before. And precising may not reflect real situation of the system because of ambiguity and vague characteristic of some basic events. To overcome this disadvantage, the fuzzy approach is combined with the analysis to evaluate the probabilities of the events (Lavasani et al., 2015; Sen et al., 2015; Yuhua and Datao, 2005).

Consequently, the fuzzy fault tree analysis may quantify the occurrence probabilities of events more accurately by reducing the uncertainty (Senol et al., 2015). From the perspective of the fuzzy logic, the occurrence possibilities of the events are questioned instead of the occurrence probabilities of the events, since the notion of the event possibility is more predictive than that of the event probability (Tanaka et al., 1983).

The concept of the fuzzy theory was first introduced by Zadeh (1965). The theory's main contribution is its capability of representing vague data (Kahraman et al., 2003). Hence, humans use the linguistic variables when assessing qualitatively or give intervals instead of exact crisp values in evaulating the data quantitatively, therefore, using the fuzzy set theory provides more explanatory studies. Decision makers usually find that it is more confident to give interval judgments than fixed value judgments as well. The fuzzy set theory makes the comparison process more confident and increases the capability of explaining preferences of the expert (Kahraman et al., 2003). The fuzzy theory uses triangular or trapezoidal fuzzy numbers to change vague data into a useful data efficiently (Lee at al., 2011) and in this study, trapezoidal fuzzy numbers (a,b,c,d) are used within the scope of the study.

To be determined occurrence probability and also consequences of the specified accidents and incidents, expert opinions are used utilizing the linguistic expressions as listed in Table 1. Each linguistic expression has an equivalent fuzzy number value for calculations also shown in the same table. According to Ford and Sterman (1998), experts will regard their objective reasoning while expressing their opinions. For this reason, it is recommended to take advantage of the heterogeneous experts for the determination of probabilities of the events (Senol et al., 2015).

Table 1: Linguistic expressions and their corresponding fuzzy numbers

Linguistic expression	(a, b, c, d)
Very low	(0, 0, 0.1, 0.2)
Low	(0.1, 0.2, 0.2, 0.3)
Slightly low	(0.2, 0.3, 0.4, 0.5)
Medium	(0.4, 0.5, 0.5, 0.6)
Slightly high	(0.5, 0.6, 0.7, 0.8)
High	(0.7, 0.8, 0.8, 0.9)
Very high	(0.8, 0.9, 1, 1)

And a weighting function is executed to increase the accuracy of the gathered data concerning probability or consequences value of each basic events of the fault tree. To be allocated a weight for each participated expert in the study, the titles of the experts, their sectoral experience, and educational backgrounds are considered. The scores for classes of the particular criteria are given in Table 2. The significance levels of experts are specified by normalizing the total of the score values concerning the experts' information.

Table 2: Score table to specify the level of significance of the experts

Criterion	Class	Score	Criterion	Class	Score	Criterion	Class	Score
Title	Manager	5	Sectoral Experience	≥ 30 years	5	Educational Status	Postgraduate	5
	Chief Engineer	4		20-29 years	4		Undergraduate	4
	Engineer	3		10-19 years	3		Associate Deg.	3
	Sergeant Major	2		6-9 years	2		High School	2
	Employee	1		≤ 5 years	1		Primary Edu.	1

We assume that i symbolizes the basic event, j symbolizes the number of experts and w_j symbolizes the level of significance of j^{th} expert. When $\tilde{A}_{ij}$ indicates the corresponding fuzzy numbers of the linguistic expression of j^{th} experts for possibility and consequence value of i basic event, to aggregate the opinions of the experts under a single value as $\tilde{A}_i^*$, following equation is used:

$$\tilde{A}_i^* = (a, b, c, d) = \sum_{j=1}^{m} w_j * \tilde{A}_{ij}(a, b, c, d) \quad (1)$$

After gathering the experts' opinions for possibilities and consequences of the events, fuzzy numbers need to be defuzzification. Apart from different techniques for this calculation, the center of area method developed by Sugeno (1999) is used. When $\tilde{A}_i^*$ = (a, b, c, d) is the joint fuzzy evaluation by the experts for i event, and converting of the fuzzy number $\tilde{A}_i^*$ to X* classical numerical value is as below:

$$X^* = \frac{1}{3} \times \frac{(d+c)^2 - d \times c - (a+b)^2 + a \times b}{(d+c-a-b)} \quad (2)$$

X^* represents the final value for an event's consequence but to find out the final value for probabilities X^* values are converted into the precise values by the operation below (Onisawa and Nishiwaki, 1988). In this stage, possibility values of the events are also converted into the probability values of the events.

$$\text{Final probability value for the event } = \begin{cases} \frac{1}{10^K}, & X* \neq 0 \\ 0, & X* = 0 \end{cases} \quad (3)$$

where,

$$K = \frac{\left[\frac{1-X^*}{X^*}\right]^{\frac{1}{3}}}{} \times 2.301 \quad (4)$$

After assessment of the basic events' probabilities, the probability's of the minimal cut sets which belong to undesired events are determined. It is accepted that there is the "Boolean relationship" for the occurrence of the events and all basic events are independent of each other (Lavasani *et al.*, 2015). If E_1 and E_2 events are connected by AND gate in a minimal cut set (MC), it is indicated as $MC = E_1 \cap E_2$. The probability is as $P(MC) = P(E_1 \cap E_2) = P((E_1) \times (E_2))$. If E_1 and E_2 events are connected by OR gate in a minimal cut set, it is indicated as $MC = E_1 \cup E_2$. The probability of the minimal cut set is as $P(MC) = P(E_1 \cup E_2) = P(E_1) + P(E_2) - P(E_1 \cap E_2)$, $P(MC) = P(E_1) + P(E_2) - P\big((E_1) \times (E_2)\big)$. If the probability of accident's occurrence is indicated as $P(t)$ in the system stated as top event, the combination set of N pieces cut set bearing necessary and sufficient conditions for the accident's occurrence is as below (Senol *et al.*, 2015):

$$P(t) = P\big(\cup_{j=1}^{N} MC_j\big), \quad P(t) = \sum_{i=1}^{N} P(MC_i) - \sum_{i<j}^{N} P\big(MC_i \times MC_j\big) + \sum_{i<j<k}^{N} P\big(MC_i \times MC_j \times MC_k\big) + \cdots + (-1)^{N-1} P(MC_1 \times MC_2 \times \ldots \times MC_N) \quad (5)$$

3.3. Determining the consequences of the undesired events

Mining accidents may have detrimental effects on workers in the form of injury, disability or fatality as well as mining company due to downtimes, interruptions in the mining operations, equipment breakdowns, etc. (Düzgun and Einstein, 2004). In this study, as consequences of the undesired events, the influence severity of the undesired events on the employees is considered. Therefore, the possible consequences are accepted as no harm, incapacity for a few hours, incapacity for full-time, incapacity for a week, two weeks and a month, incapacity for quite a while, permanent incapacity and death from the least to severest one respectively. Different expert opinions through the fuzzy approach are used to evaluate the events' consequences as mentioned before. By adjusting the linguistic expressions about the consequences according to fuzzy logic properly as stated in Table 3, the experts are questioned to specify the severity of the event's possible influence on employees. Also, for converting the gathered fuzzy value for the consequences to the classical numerical value, given calculation method is used.

Table 3: Linguistic expressions and equivalent value for the consequences

Influence severity	Equivalent for the consequences
Very low	No harm or incapacity for a few hours
Low	No harm, incapacity for a few hours or incapacity for full-time
Slightly low	No harm, incapacity for a few hours, incapacity for full-time or incapacity for a week
Medium	Incapacity for a few hours - two week
Slightly high	Incapacity for a month
High	Incapacity for quite a while or permanent incapacity
Very high	Incapacity for quite a while, permanent incapacity or death

3.4. Risk analysis

Underground mines have a considerable number of hazard elements that cause the accidents and incidents. Major risk elements in mines are challenging working conditions and the processes which are mostly in human control. The undesired events are geological structure and human-related accidents and incidents as it is in all other mines. Apart from these, the above unsafe conditions for all mines might be listed as dust, fume, water, mud, inadequate ventilation as well as harsh working conditions and psychological effect of working in the underground. Thus, the considerable number of hazardous situations that cause the accidents and incidents may occur, and no matter how much risk level these dangerous elements have, they constitute a threat to occupational health and safety.

The aim of this study is performing a risk analysis of mentioned hazardous operations using the fault tree analysis and the fuzzy approach. As mention before, the fault tree analysis includes both qualitative and quantitative analysis. In the qualitative part, minimal cut sets that comprise the necessary conditions to happen an accident and incidents are specified. In the quantitative part, the probabilities of the undesired events illustrated with minimal cut sets are expressed in terms of the occurrence probability of the basic events. In order to evaluate the risk involved in undesired events, the probabilities and the consequences which are the main components of the risk analysis have to be quantified. For quantifying the risk components, different experts being consulted is projected by using the effectiviness of the fuzzy approach's advantage. After determining the consequences values of the specified undesired events in conjunction with the probabilities, risk analysis can be performed easily. By multiplying these values for each specified undesired event, sorting the events from the riskiest to the least risky one can be possible. For this study, risk is defined by probability of occurrence of an undesired event times the consequences if the event occurs on employees.

When the managements are conscious of the risky situation, events, processes, locations, departments or human behaviours, they can prevent or mitigate the accidents and incidents which may harm to processes or the employees. Due to the crucial importance of the considering the risk analysis, firstly the most convenient methods are specified for the case. The proposed methodology in this study, is quite suitable to define the variety accidents ad incidents in a process detailed. Especially in hazardous sectors as mining or construction sectors, not just be focused the most tragic accidents, all possible undesired events should be considered in risk analysis. Therefore, this proposed methodology primarily aims to disclosed the all possible undesired events and analyse them with regards to their risk level by using a practicable method. The next section is about the implementation of the methodology to a chrome mine's particular process.

4. Application of risk analysis methodology for an underground chrome mine

The proposed methodology within the concept of the study is implemented to an underground chrome mine located in the middle of the Turkey. Since the limited past accident data of the mining firms and to provide the accuracy of the analysis, just activities in underground loading and conveying processes of the mine are handled to perform risk analysis. According to the methodology, the 4 stages of risk analysis are presented as following.

4.1. Creating the fault tree and specifying the undesired events with their minimal cut sets.

"Undesired events during underground loading and conveying activities of the chrome mine" are described as top events for constructing the fault tree. Loading of the mine and conveying to the surface activities are maintained collectively. Upon interviews with the experts, underground loading and conveying activities of the mine are stated as seen in Figure 3.

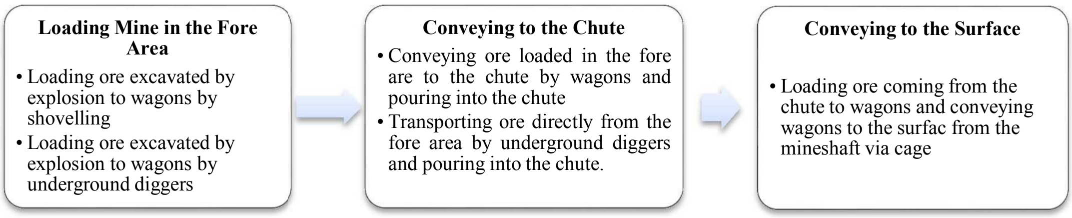

Figure 3: Activity flow for underground loading and conveying of mine

By consulting with the experts, the fault tree has structured in a top-down manner comprehensively. It is considered that all the undesired events that may harm to employees already occurred in the past and having the probability to happen in the future according to experts need to be included in the fault tree. For this purpose, the flow diagram of the process is composed as in Figure 3, and the dividing the top event according to the sub-processes is considered. Similarly, in Liu *et al*. study (2016), the accidents in coal mines are investigated by dividing the entire coal enterprise into several subsystems as coal mining department, driving department, electromechanical department or transportation department, etc. Therefore, in this analysis, we take into account underground loading and conveying processes and divide them into several subsections and the top of the fault tree is constructed as seen in Figure 4. After implementing a series of expert consultations for the constructing of the fault tree, finally the fault tree is constructed as Figure 5. Possible undesired events during particular underground processes of mine which might be resulting in cuts, wounds, scratches, bruises, fractures, dislocations, sprains, temporary or permanent incapacity and those involving death are specified and presented in the subsections of the fault tree. The basic events and the intermediary events of the fault tree are listed in Table 4 and the Table 5 respectively. And the undesired events which may harm to employees will be performed are listed in Table 6.

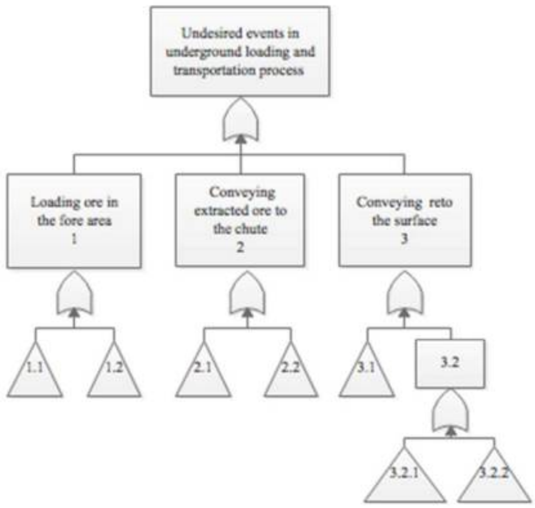

Figure 4: The top of the fault tree for the particular processes of the mine

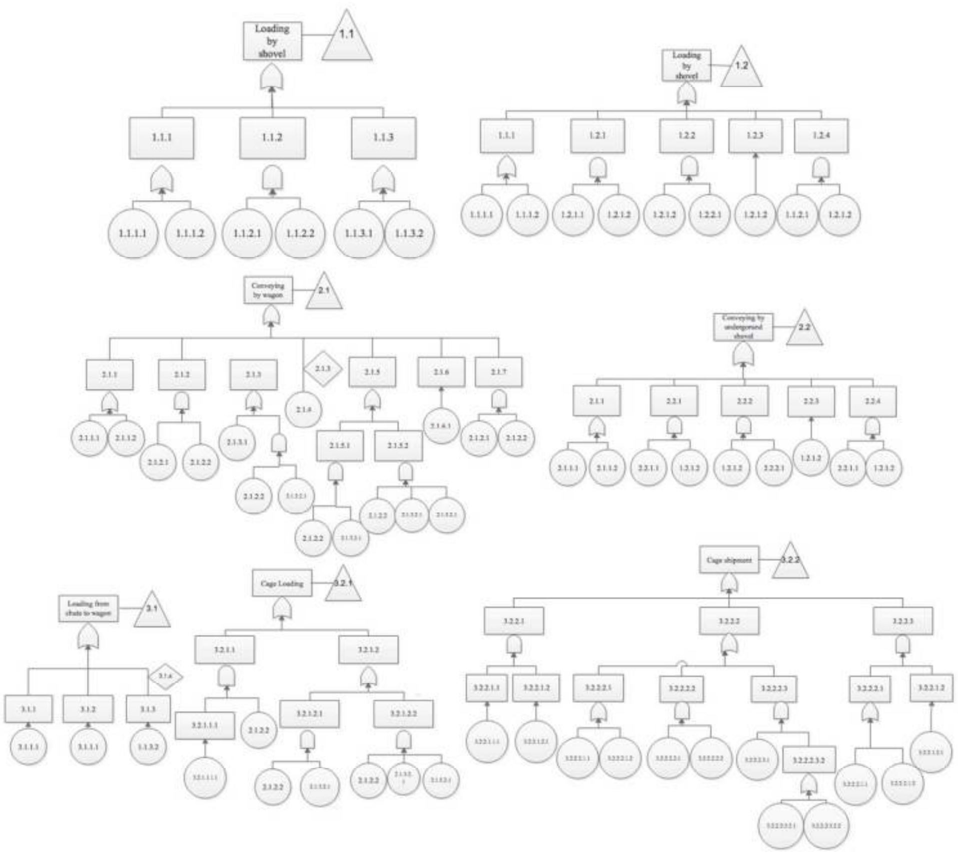

Figure 5: The subsections of the fault tree

Table 4: Basic events

1.1.1.1	Geological structural cleavage in the fore area	2.1.2.1	Rugged conveying drift	3.2.1.1.1.1	Fail to comply instructions for cage loading
1.1.1.2	Insufficient scale control in the fore area	2.1.2.2	Wagon operator's lack of attention	3.2.2.1.1.1	Insufficient control of crane rope
1.1.2.1	Rugged ground	2.1.3.1	Wear of railroad	3.2.2.1.2.1	Poor maintenance of brake system
1.1.2.2	Inattention of fore employee	2.1.3.2.1	Wagon operator's failure to comply speed instructions	3.2.2.2.1.1	Poor maintenance of control system
1.1.3.1	Overload during shovelling, fail to comply instructions	2.1.4	Physical constraints	3.2.2.2.1.2	Operator's failure to adjust controls
1.1.3.2	Rugged ground to affect digger in the fore area	2.1.5.2.1	Inattention of the employee working on road	3.2.2.2.2.1	Wear of support system
1.2.1.1	Uncontrolled picking of materials by hand	2.1.6.1	Fail to comply wagon load instructions (overload)	3.2.2.2.2.2	Insufficient control of support system
1.2.1.2	Inattention of the digger operator	2.2.1.1	Digger road's being rugged	3.2.2.2.3.1	System breakdown
1.2.2.1	Inattention of the fore employee	2.2.2.1	Inattention of the employee working on digger road	3.2.2.2.3.2.1	Poor maintenance of generator/mec. breakdown
2.1.1.1	Geological structural cleavage on conveying	3.1.1.1	Wagon operator's failure to comply instructions while receiving materials	3.2.2.2.3.2.2	Insufficient gasoline/control
2.1.1.2	Insufficient control along road				

Table 5: Intermediary events

1.1	Loading by shovel	2.1.5 2	Entrapment of someone else by operator pushing wagon	3.2.1.1	Fall of wagon to the pit
1.1.1	Fall of scales	2.1.6	Fall of materials on operator pushing wagon	3.2.1.1.1	The cage gate's being open
1.1.2	Fall of employee while working with shovel	2.1.7	Fall of employee to the chute	3.2.1.2	Wagon entrapment accidents in the cage
1.1.3	Employee's physical constraint	2.2	Conveying by underground digger	3.2.1.2.1	Operator pushing wagon's entrapment between two other wagons
1.2	Loading by digger	2.2.1	Rollover of digger on conveying drift	3.2.1.2.2	Entrapment of someone else by the operator pushing wagon in the cage
1.2.1	Rollover of digger	2.2.2	Digger's hit to employees on conveying drift	3.2.2	Cage shipment
1.2.2	Digger's hit to employees in the fore area	2.2.3	Digger's hit to support on conveying drift	3.2.2.1	Fall of the cage to space
1.2.3	Digger's hit to support	2.2.4	Fall of operator from digger on conveying drift	3.2.2.1.1	Rope breakage
1.2.4	Fall of digger's operator	3.1	Loading from chute to wagon	3.2.2.1.2	Breakdown of automatic brake system
2.1	Conveying by wagon	3.1.1	Fall of materials on employees from the chute	3.2.2.2	The cage's being hanged in the air
2.1.1	Fall of scales on conveying drift	3.1.2	Scaling bar injuries	3.2.2.2.1	Failure of control system of crane
2.1.2	Fall of operator pushing wagon	3.1.3	Material picking injuries	3.2.2.2.2	Hanging the cage on pit supports
2.1.3	Derail of wagon	3.1.4	Fall of materials on the ground	3.2.2.2.3	Power outage
2.1.5	Wagon entrapment accidents	3.2	Reach of wagon to the surface	3.2.2.2.3.2	Breakdown of generator
2.1.5.1	Entrapment of operator pushing wagon	3.2.1	Cage loading	3.2.2.3	The cage's hit to the ceiling

Table 6: Undesired events specified by the experts

1	1.1.1.	Fall of scales on employee in the fore area	15	2.1.7	Fall of employee to the chute
2	1.1.2	Fall of employee while working with shovel	16	2.1.1'	Fall of scales on conveying drift on digger operator
3	1.1.3	Employee's physical constraint	17	2.2.1	Rollover of digger on conveying drift
4	1.1.1'	Fall of scales on digger operator in the fore area	18	2.2.2	Digger's hit to employees on conveying drift
5	1.2.1	Rollover of digger	19	2.2.4	Fall of operator from digger on conveying drift
6	1.2.2	Digger's hit to employees in the fore area	20	3.1.1	Fall of materials on employees from the chute
7	1.2.4	Fall of digger's operator	21	3.1.2	Scaling bar injuries
8	2.1.1	Fall of scales on conveying drift on operator pushing wagon	22	3.1.3	Material picking injuries
9	2.1.2	Fall of operator pushing wagon	23	3.2.1.1	Fall of wagon to the pit
10	2.1.3	Incident of operator pushing wagon cause of derail of wagon	24	3.2.1.2.1	Operator pushing wagon's entrapment between two other wagons
11	2.1.4	Physical constraints of operator pushing wagon while relocating of the derailed wagon	25	3.2.1.2.2	Entrapment of someone else by the operator pushing wagon in the cage
12	2.1.5.1	Entrapment of operator pushing wagon	26	3.2.2.1	Fall of the cage to space
13	2.1.5.2	Entrapment of someone else by	27	3.2.2.2	The cage's being hanged in the air
14	2.1.6	Fall of materials on operator pushing wagon	28	3.2.2.3	The cage's hit to the ceiling

Within the scope of the qualitative side of the fault tree analysis, minimal cut sets for each undesired events also need to be specified. A minimal cut set is the smallest set of basic events, which if they all occur will result in one of the undesired events stated in Table 6. For example, to occur the "2.2.1 event - rollover of the digger on the conveying drift", the basic events "2.2.1.1" and "1.2.1.2" need to occur together and this minimal cut set is an example of the second order cut set. The minimal cut sets of all undesired events of this study are until the third order as shown in Table 7.

Table 7: Minimal cut set for each undesired event

No.	Code of undesired event	Minimal cut set of the undesired event	No.	Code of undesired event	Minimal cut set of the undesired event
1	1.1.1.	1.1.1.1., 1.1.1.2.	15	2.1.7	(2.1.2.1. AND 2.1.2.2.)
2	1.1.2	(1.1.2.1. AND 1.1.2.2.)	16	2.1.1'.	2.1.1.1., 2.1.1.2
3	1.1.3	1.1.3.1., 1.1.3.2.	17	2.2.1	(2.2.1.1. AND 1.2.1.2.)
4	1.1.1'.	1.1.1.1., 1.1.1.2.	18	2.2.2	(1.2.1.2. AND 2.2.2.1.)
5	1.2.1	(1.2.1.1. AND 1.2.1.2.)	19	2.2.4	(2.2.1.1. AND 1.2.1.2.)
6	1.2.2	(1.2.1.2. AND 1.2.2.1.)	20	3.1.1	3.1.1.1
7	1.2.4	(1.1.2.1. AND 1.2.1.2.)	21	3.1.2	3.1.1.1
8	2.1.1	2.1.1.1., 2.1.1.2	22	3.1.3	(1.1.3.2. AND 3.1.4.)
9	2.1.2	2.1.2.1. AND 2.1.2.2.	23	3.2.1.1	(3.2.1.1.1.1. AND 2.1.2.2.)
10	2.1.3	2.1.3.1., (2.1.2.2. AND 2.1.3.2.1)	24	3.2.1.2.1	(2.1.2.2. AND 2.1.3.2.1.)
11	2.1.4	(2.1.4. AND 2.1.3.)	25	3.2.1.2.2	(2.1.2.2. AND 2.1.3.2.1. AND 2.1.5.2.1.)
12	2.1.5.1	(2.1.2.2. AND 2.1.3.2.1.)	26	3.2.2.1	(3.2.2.1.1.1. AND 3.2.2.1.2.1.)
13	2.1.5.2	(2.1.2.2. AND 2.1.3.2.1. AND 2.1.5.2.1.)	27	3.2.2.2	3.2.2.2.1.1., 3.2.2.2.1.2., (3.2.2.2.2.1. AND 3.2.2.2.2.2.), (3.2.2.2.3.1. AND 3.2.2.2.3.2.1.), (3.2.2.2.3.1. AND 3.2.2.2.3.2.2.)

14	2.1.6	2.1.6.1	28	3.2.2.3	(3.2.2.2.1.1. AND 3.2.2.1.2.1.), (3.2.2.2.1.2. AND 3.2.2.1.2.1.)

4.2. Determining the probabilities of the undesired events.

To be performed the risk analysis as expressed in the methodology section, probabilities and consequences of the events which are the main components of the risk analysis need to be determined. For the construction of the fault tree and performing the quantitative part of the study, a heterogeneous expert group which comprises five experts are consulted from a firm that its operations for chrome mine. The mining firm located in the middle of the Turkey and the mine's extracted chrome is demanded as quality metallurgical ore in the chrome markets with high prices.

The required information about the experts to determine their importance weights are presented in Table 8.

Table 8: Participated experts and the importance weights

No. of experts	Position	Experience	Level of Education	Level of Significance
1	Manager	10-19 years	Postgraduate	0.29
2	Chief Engineer	6-9 years	Undergraduate	0.22
3	Engineer	6-9 years	Undergraduate	0.20
4	Sergeant Major	≥ 30 years	Primary Edu.	0.18
5	Employee	10-19 years	Primary Edu.	0.11

The experts' levels of significance are determined following the scores stated in Table 2, and the importance scores of them are shown in the last column of Table 8. Then, it is ensured that they have carried out the evaluations with the help of the linguistic expressions stated in Table 1, regarding the probabilities of occurrence of the basic events reported in Table 4. The minimal cut set of each undesired event listed in Table 6 is specified and given in Table 7. It is found out that 28 different undesired events may occur and harm to the employees under the underground and conveying processes of the mine. By considering the minimal cut set of each undesired event and the calculation method mentioned in the methodology section, the occurrence probabilities of the events are calculated according to the different experts' judgments, and results are presented in Table 9. Upon analysis, events which are the top five occurrence probability can be stated as employee's physical constraint while working in the fore are by shovel, fall of materials on employees from the chute, scaling bar injuries, fall of scales on employee in the fore area and fall of scales on digger operator in the fore area, respectively. All these undesired events have the first order minimal cut set, and they have the highest occurrence probability as expected.

4.3. Determining the consequences of the undesired events

Underground loading and conveying processes of the chrome mine which are maintained mostly by labour-intensive are handled, and undesired events that can harm to employees are considered for risk analysis. After specifying the many undesired events with their occurrence probabilities using fault tree analysis and fuzzy approach, the level of influences which are directed at employees are taken into account, when evaluating the consequences of the accidents and incidents. As mentioned in the methodology section, the participant experts are consulted about the possible consequences of the undesired events. The consequences values of the undesired events are shown in Table 9. For calculation, linguistic expressions and fuzzy equivalent values of them as shown Table 1 and Table 3 are used. According the table, the events which have the severest consequences are the falling of the employee to the chute, the falling of the cage to pit bottom and hitting the cage to the ceiling respectively. It is already quite possible to indicate that the most serious accidents are about the chute and the cage in an underground mine because of the special dangerous nature of the places.

4.4. Risk analysis

Within the scope of the study, the all undesired events that can occur during the underground loading and conveying processes of the mine are specified with the fault tree analysis. After determining the probabilities and the consequences of the events with the fuzzy approach, the risk analysis is performed. The results about the risk values of the events are given in Table 9. According to the table, employee's physical constraint while working with a shovel in the fore area, the falling of materials on employees from the chute and the scaling bar injuries are explored as the riskiest undesired events in the mine's underground loading and conveying process. Similarly, a study which analyses the recorded accidents in the Spanish mining sector, physical effort is represented as one of the primary cause of the accident (Sanmiquel et al., 2015). When investigating the basic events of the undesired events specified as the riskiest according to the results, it is shown that the basic causes of accidents or incidents in an underground mine are shown as the nature of the underground compelling working conditions, geological structure of the mine and the human behavior and attention. Our findings are consistent with the literature. For example, Sanmiquel et al. (2015) stated that the most immediate causes of the accident are related to poor conditions of the workplace and the behavior of the employees and Groves et al.'s (2007) specified that the injuries associated with the scaling bars are one of the most frequent occurred accidents. Therefore, the human factors about being inattention or failing to comply the instruction are the key factors causing an accident or incident in the underground mines, which provides references and basis for the prevention work for such accidents in future. In addition to this, the processes in the chute and the cage area should be reviewed detailed to prevent the possible disaster by the mine managements.

Table 9: The probability, consequence and final risk scores of the undesired events

	Undesired Event	Probability	Consequence	Risk	Ranking of Probability	Ranking of Consequence	Ranking of Risk
1.1.1.	Fall of scales on employee in the fore area	0,030163835	0,369940239	0,011158816	**4**	17	**4**
1.1.2	Fall of employee while working with shovel	2,52826E-05	0,320195373	8,09536E-06	13	18	12
1.1.3	Employee's physical constraint	0,082298328	0,5465	0,044976037	**1**	8	**1**
1.1.1'	Fall of scales on digger operator in the fore area	0,030163835	0,077777778	0,002346076	**5**	27	6
1.2.1	Rollover of digger	2,52918E-06	0,3965	1,00282E-06	15	16	15
1.2.2	Digger's hit to employees in the fore area	4,40683E-09	0,4565	2,01172E-09	20	11	21
1.2.4	Fall of digger's operator	1,5556E-05	0,3065	4,76791E-06	14	19	13
2.1.1	Fall of scales on conveying drift on operator pushing wagon	0,001900169	0,271363881	0,000515637	8	23	8
2.1.2	Fall of operator pushing wagon	2,4859E-09	0,3065	7,61927E-10	21	20	23
2.1.3	Incident of operator pushing wagon cause of derail of wagon	0,011869413	0,59	0,007002954	6	7	**5**
2.1.4	Physical constraints of operator pushing wagon while relocating of the derailed wagon	0,001162397	0,40007109	0,000465042	11	15	10
2.1.5.1	Entrapment of operator pushing wagon	3,12199E-08	0,44	1,37368E-08	16	13	17
2.1.5.2	Entrapment of someone else by	8,66134E-13	0,3065	2,6547E-13	27	21	27
2.1.6	Fall of materials on operator pushing wagon	0,007593193	0,263303514	0,001999314	7	25	7

2.1.7	Fall of employee to the chute	2,4859E-09	0,869645051	2,16185E-09	22	**1**	20
2.1.1'	Fall of scales on conveying drift on digger operator	0,001900169	0,271363881	0,000515637	9	24	9
2.2.1	Rollover of digger on conveying drift	1,0025E-08	0,7235	7,25308E-09	18	**5**	18
2.2.2	Digger's hit to employees on conveying drift	8,99468E-10	0,5465	4,91559E-10	24	9	24
2.2.4	Fall of operator from digger on conveying drift	1,0025E-08	0,44	4,411E-09	19	14	19
3.1.1	Fall of materials on employees from the chute	0,04849897	0,6065	0,029414625	**2**	6	**2**
3.1.2	Scaling bar injuries	0,04849897	0,5465	0,026504687	**3**	10	**3**
3.1.3	Material picking injuries	0,001581755	0,141226238	0,000223385	10	26	11
3.2.1.1	Fall of wagon to the pit	2,41694E-09	0,757930403	1,83187E-09	23	**4**	22
3.2.1.2.1	Operator pushing wagon's entrapment between two other wagons	3,12199E-08	0,4565	1,42519E-08	17	12	16
3.2.1.2.2	Entrapment of someone else by the operator pushing wagon in the cage	8,66134E-13	0,3065	2,6547E-13	28	22	28
3.2.2.1	Fall of the cage to space	3,20646E-11	0,844930403	2,70924E-11	26	**2**	26
3.2.2.2	The cage's being hanged in the air	3,56305E-05	0,077777778	2,77126E-06	12	28	14
3.2.2.3	The cage's hit to the ceiling	1,89161E-10	0,801543554	1,51621E-10	25	**3**	25

5. Conclusion and Recommendations

Important technological innovations beginning from the 17th century have pioneered significant developments for the sustainability of mining (Suppen et al., 2006). Stages of use of high technology for mining activities in the world are mechanization, remote steering systems, automation and robotisation respectively (Kızıl et al., 1995). In literature, studies are arguing where mining with the advanced automation technologies come (Boudreau et al., 2014; Bellamy and Pravica, 2011). However, operations of the mining sector in many countries are maintained by small-sized enterprises and by labour-intensive activities. In all mines, there are many hazardous conditions need to be analyzed for preventing and mitigating them. No matter how severe and probable they are, preventing the underground mining accidents and incidents is one of the most important objectives of mine administrators. It is inevitable to urge upon the issues such as necessary audits, accident preventing systems and appropriate technology for the avoidance of occupational accidents and physical injuries in the mining sector (Paul and Maiti, 2007; Maiti et al., 2004). To reduce and prevent the occurrence of the accidents and incidents, reasons of these undesired events have to be understood and mastered fully to provide a reference for further corrective measures (Jiang et al., 2012).

For the purpose of the study, 28 undesired events in loading and conveying processes of the underground mine are specified and analyzed from the risk perspective by using the proposed methodology. To our knowledge, this is the first study that takes into account the chrome mining operations in detail. For following studies about the mining, detailed risk mitigation investigations are suggested about these undesired events and their specified primary causes. It is not a coincidence that mines with safer work conditions report less occupational accidents, together with better percentages of competitiveness (Sanmiquel et al., 2015).

In this study; the matter not only is considered for the mining sector; but also considered for hazards, risky activities, accidents and safety concepts in many different sectors. The safety management in the organizations is always searching methods for risk mitigation and sometimes they may always focus the same point in the organizations and can not realize other critical risk points. So, in this study, we proposed a comprehensive methodology that includes the fault tree analysis and fuzzy approach. By using the fault tree analysis, the possible undesired events with their causes in a particular process may be found out effectively, and fuzzy approach provides for accounting the linguistic expressions of experts about the events' risk components for quantitative analysis, accomplishedly. Thus, the developed methodology can be performed efficiently for variety study fields to define the major and minor undesired events and analyze them from a common risk perspective without statistical data. For future research, application of the proposed methodology to different processes in mines or another hazardous operations for different sectors are suggested.

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