RISK ASSESSMENT BY FAULT TREE ANALYSIS OF ROOF AND RIB FALL ACCIDENTS IN AN UNDERGROUND HARD COAL MINE

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ABSTRACT

RISK ASSESSMENT BY FAULT TREE ANALYSIS OF ROOF AND RIB FALL ACCIDENTS IN AN UNDERGROUND HARD COAL MINE

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Mining sector has a high rate of injury and fatality among other sectors. Roof and rib fall in underground mines is one of the most commonly encountered accident causes that results in injuries, permanent disabilities, even fatalities. Implementing effective prevention measures based on the quantitative risk assessment is an emerging issue for underground coal mines in Turkey. The main objective of this study is to determine the root causes of roof and rib fall accidents in underground coal mines by implementing quantitative risk assessment. This objective was achieved by evaluating the accidents occurred due to roof and rib falls from years 2003 to 2013 in the selected pilot research area, Turkish Hard Coal Enterprise (TTK) – Amasra Hard Coal Institution. In order to determine root causes of roof and rib falls, fault tree analysis (FTA) methodology was implemented.

The methodology starts with the preprocessing of acquired data and determination of the main causes and consequences of roof and rib falls in Amasra underground coal mine. Then intermediate and basic events of fault tree were identified and fault tree for roof and rib fall accidents was generated. The risks associated with each basic event and cuts sets of fault tree were computed using ReliaSoft BlockSim-7 software. Finally, major causes of roof and rib fall accidents were determined according to the computed risks.

Research findings revealed that causes with the highest static reliability importance are improper personal protective equipment (PPE), procedural errors, and improper tools. This study, as being the first implementation of FTA in underground roof and rib fall accidents, is expected to contribute to mining industry and current literature in various ways. The developed accident database could be extended further to create a national mine accident database. In future studies, the developed risk analysis methodology could be used in other mines of TTK and also in other underground coal mines to decrease the risk of roof and rib falls and consequently decreasing the injury and fatality rates. The results of this study should be considered in preparing a ground control risk assessment plan for the particular coal mine and other underground hard coal mines as well.

Keywords: Fault Tree Analysis (FTA), roof and rib falls, underground hard coal mine, occupational health and safety (OHS), risk assessment

ÖZ

BİR YERALTI TAŞ KÖMÜRÜ MADENİNDE TAŞ VE KAVLAK DÜŞMELERİNDEN KAYNAKLANAN KAZALARIN HATA AĞACI ANALİZİ YÖNTEMİYLE RİSK DEĞERLENDİRMESİ

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Maden sektöründeki yaralanma ve ölüm oranları diğer sektörlere kıyasla daha fazladır. Yeraltı madenlerinde meydana gelen taş ve kavlak düşmeleri ise en fazla karşılaşılan kaza nedenlerinden biridir ve bu kazalar yaralanma, sakatlık ve hatta ölümle sonuçlanabilmektedir. Kantitatif risk değerlendirmelerine dayalı etkili koruma tedbirlerinin uygulanması Türkiye'deki yeraltı kömür madenleri için gelişmekte olan bir konudur. Bu çalışmanın amacı, yeraltı kömür madenlerinde taş ve kavlak düşmelerinden kaynaklanan yaralanmaların ana nedenlerinin belirlenmesidir. Bu amaç, 2003-2013 yılları arasında taş ve kavlak düşmesi kazalarının, seçilen pilot araştırma sahası olan Türkiye Taşkömürü Kurumu (TTK) – Amasra Taşkömürü İşletme Müessesinde incelenmesi sonucunda belirlenmiştir. Taş ve kavlak düşmelerinin kök nedenlerinin bulunması amacıyla hata ağacı analizi (FTA) metodu uygulanmıştır.

İlk olarak elde edilen veriler işlenerek, Amasra yeraltı kömür madeninde gerçekleşen taş ve kavlak düşmelerinin ana nedenleri ve bunların sonuçları belirlenmiştir. Daha

sonra ara ve esas olaylar tespit edilerek, taş ve kavlak düşmelerinden kaynaklanan yaralanmaların hata ağacı analizi oluşturulmuştur. Her ana olaydan kaynaklanan riskler ve hata ağacını oluşturan minimal cut setler ReliaSoft BlockSim 7 programı kullanılarak bulunmuştur. Son olarak taş ve kavlak düşmelerinden kaynaklanan yaralanmaların nedenleri hesaplanan risklere göre tespit edilmiştir.

Araştırma sonucunda taş ve kavlak düşmelerinin nedenleri arasında statik güvenilirlik önemi en yüksek olanlar uygun olmayan kişisel koruyucu donanım (KKD), prosedür hataları ve uygun olmayan aletler olarak tespit edilmiştir. Bu çalışma yeraltında taş ve kavlak düşmelerinin hata ağacı analizi kullanılarak bulunmasının ilk örneğini oluşturmakta ve bu bağlamda maden endüstrisine ve literatüre katkıda bulunması beklenmektedir. Düzenlenen kaza veri tabanı geliştirilerek ulusal bir maden kaza veri tabanı oluşturulmasına katkıda bulunabilir. Gelecek çalışmalarda, uygulanan bu hata ağacı analizi TTK'nın diğer madenlerinde de kullanılabilir ve aynı zamanda diğer yeraltı kömür madenlerinde taş ve kavlak düşmesinden kaynaklanan risklerinin azaltılması ve bunun sonucunda yaralanma ve ölümlü kazaların azaltılması için de kullanılabilir. Bu çalışmanın sonuçları özellikle bu pilot maden sahası ve aynı zamanda diğer yeraltı taşkömürü madenleri için de zemin kontrolü risk değerlendirme planı hazırlanırken göz önünde bulundurulmalıdır.

Anahtar Kelimeler: Hata Ağacı Analizi (FTA), taş ve kavlak düşmesi, yeraltı taşkömürü madeni, iş sağlığı ve güvenliği (İSG), risk değerlendirmesi

To my parents

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CHAPTER 1

INTRODUCTION

1.1 Background Information

According to International Labor Organization (ILO), for every 15 seconds, a worker losses his/her life due to a work-related accident and/or disease (ILO, 2014). Mining is one of the most hazardous industries due to the inherent risk involved in development and production operations. Turkey, as one of the global players in the mining industry, has experienced tragic mine disasters for many decades. Turkish Social Security Institution (SGK) yearly statistics showed that there have been 9,225 permanent injuries and 5,924 fatalities between the years of 2008 and 2012. When it was analyzed on a sectoral basis, it was seen that in 2012, coal and lignite mining operations ranked first in the occupational injury with 8,828 injuries, and eighth in permanent incapability (SGK, 2012).

In underground coal mines, roof and rib fall is also a significant reason of injuries and fatalities both in Turkey and in other countries. For example, more than 800 workers got injured by roof and rib falls in the U.S. coal mines in 1997 (Bauer and Dolinar, 1999). Also, from 1999 through 2008 there were 75 fatalities and 5,941 injuries occurred due to roof fall in underground coal mines in the U.S. (Pappas and Mark, 2012).

Between 2003 and 2013 in underground hard coal mines, there were 5,115 injuries occurred due to roof and rib falls, only in four mine sites, namely Armutçuk, Amasra, Kozlu and Üzülmez according to the accident data gathered from Turkish Hard Coal Enterprise (TTK) (Table 1.1). Since it is a major cause of fatalities, injuries and production losses, risks associated with roof and rib falls should be investigated in detail and root causes of them should be evaluated in order to prevent such accidents and decrease the accident rates in underground coal mines.

Table 1.1 Number of Occupational Accidents from 2003 to 2013 in TTK

Accident Causes	Armutçuk	Amasra	Kozlu	Üzülmez
Roof and Rib Fall	1,252	879	986	1,998
Material Usage	511	390	587	600
Transport	119	113	125	237
Machinery and Electricity	21	62	23	67
Hazardous Gasses	0	5	14	3
TOTAL	**2,819**	**2,365**	**4,963**	**4,637**

1.2 Objectives and Scope of the Study

The main objective of this research study is to implement fault tree analysis (FTA) for evaluating all the reasons for roof and rib fall accidents in an underground hard coal mine. The scope of this research study includes the injuries and fatalities occurred in the Amasra Hard Coal Institution of Turkish Hard Coal Enterprise (TTK) through 2003 to 2013. The other mines of TTK were not studied due to the lack of reliable accident records.

Components in order to achieve the objective are listed as:

(i) Obtaining data that include all occupational injuries and fatalities occurred in TTK underground hard coal mines,

(ii) Creating a database related to roof and rib fall accidents occurred in Amasra underground coal mine,

(iii) Conducting a Fault Tree Analysis for roof and rib falls for Amasra underground coal mine in order to determine the main reasons of roof and rib falls and to find reasonable solutions of preventive measures,

(iv) Developing a roof and rib fall prevention policy based on the obtained research results.

1.3 Research Methodology

In this study, sub reasons of roof and rib falls in Turkish Hard Coal Enterprise – Amasra Hard Coal Institution were analyzed. These analyses were conducted using fault tree analysis software called BlockSim© 7 (2011) and probabilistic software called Weibull++ 7 (2011) both developed by ReliaSoft Corporation. The research methodology followed essentially entails seven main stages as:

1. Preprocessing of acquired data,
2. Determination of the main causes and consequences of roof and rib falls in Amasra underground coal mine,
3. Generating intermediate and basic events of fault tree that causes roof and rib fall accidents in the research area,
4. Generating fault tree for roof and rib fall accidents using ReliaSoft BlockSim-7 software,
5. Evaluating the risks that could be occurred due to roof and rib falls,
6. Determination of the probability distributions of each basic events and cut sets by using ReliaSoft Weibull++7 software, and
7. Determining the major causes of roof and rib fall accidents, according to probability of occurrences.

1.4 Expected Contributions of the Study

The research study proposes a risk analysis of roof and rib fall accidents in an underground hard coal mine using fault tree analysis method. The first contribution of the study is that it is the first application of a comprehensive quantitative risk analysis method in the specific mine site using fault tree analysis method. In addition to this, the current literature lacks information related to the application of fault tree analysis in quantitative risk analysis on roof and rib fall accidents in underground mines. This study constitutes a first example in this context.

The main expected industrial contribution of the study is that the developed accident database could be extended further to create a national mine accident database. In the future studies, the developed risk analysis methodology could be used in other mines of TTK, and also in other underground coal mines to decrease the risk of roof and rib falls, and by this means decreasing the injury and fatality rates related to roof and rib falls.

1.5 Outline of the Thesis

This thesis is composed of five chapters. Following the introductory chapter, Chapter 2 presents a comprehensive literature survey. This literature research includes information about occupational health and safety both in the world and in Turkey by describing the evolution of occupational health and safety and its current place. Then, nature of roof and rib falls in underground mining with their causes and some methodologies to cope with roof and rib fall accidents are described. Also, risk analysis and risk assessment methods are described briefly in this chapter. Then detailed information about Fault Tree Analyses (FTA) and some application of FTA in engineering are described.

The third chapter is reserved for the information about the data and the study area. Then, in Chapter 4, FTA is developed both qualitatively and quantitatively. All events that contribute the fault tree are described briefly in the qualitative FTA section, and frequencies and probability distributions of the data are calculated in the quantitative analysis section. Finally, Chapter 5 presents results of FTA and associated discussions, main conclusions drawn from the study findings, and recommendations for future studies.

CHAPTER 2

LITERATURE SURVEY

2.1 General Information

Globally, there are approximately 100 million occupational accidents and 100,000 occupational fatalities occurred each year (Page, 2009). Occupational accidents and diseases have some economic and social implications both for employers, employees and their families, societies, environment, and for the national economy. According to the ILO, more than 4% of world’s annual GDP is lost due to occupational accidents and diseases every year. It is thought that the costs of the occupational accidents and illnesses to the world economy is minimum 600 billion USD and about 5-15% of profit of companies are lost due to work accidents and occupational diseases every year (ILO, 2009).

Among occupational accidents, mining is one of the most critical sector due to the fact that it has a high rate of occupational accidents and it is one of the most hazardous occupations. However, conditions in mine sites are continuously improving throughout time. In 1880s mining sector employees faced up to many difficult conditions with minimal or nonexistent preventions for safety and health. Now, mining employees still work in the hardest conditions but health and safety preventions improved in time. According to Mine Safety and Health Administration (MSHA), in the earlier decade’s total fatalities in mining in the U.S.A. was 1,500 on average, these rates has decreased during 1990s to 100 fatalities per year (MSHA, 2012). Also, The Bureau of Labor Statistics (BLS) found that coal miners tend to have more injuries and fatalities compared to other workers in the private sector. Also, these injuries generally are more severe. In 2005 in the U.S.A., non-fatal injury and illness rate of coal miners was 11% higher than the rest of the private industry. Besides that, underground bituminous coal mining has approximately 63% higher rate of injuries than all private industry (Margolis, 2010). Also, fatality rates for mining workers was approximately 10 times the average worker populations in the United States, Australia, and New Zealand (Lenné *et al.*, 2012). Despite coal mining has the highest fatality rates, coal provides approximately 30% of primary energy needs and globally there are over 7 million people employed in this sector (Oraee *et al.*, 2011). Therefore, instead of thinking about how catastrophic the job is; safe working conditions, and proper preventive measures should be considered.

In order to consider the preventive measures, hazards present in the mining sector are needed to be evaluated. General mining hazards can be classified as:

- hazards arising from mine structure like subsidence or roof and rib fall,
- poor ventilation related and chemical hazards like presence of chemical gasses and vapor, dust, and heavy metals, or lack of sufficient oxygen in the environment,
- physical hazards including illumination, thermal comfort, vibration and noise,
- biological hazards from soil and rusty equipment, gnawing animals like rats, moisture, dampness and epidemic illnesses,
- electrical hazards, especially in underground from non-ex-proof materials,
- fire and explosion hazards,
- hazards originated from machinery and transportation,
- ergonomic hazards, and
- psychosocial hazards.

Among these hazards, most of the accidents, especially in underground mining occur because of roof and rib falls, subsidence, fire, gas and/or rock outburst and explosion. Roof and rib fall in underground coal mining is one of the major causes of fatalities and injuries. According to National Institute of Occupational Safety and Health (NIOSH) (2011), between 1999 and 2008 in the U.S.A., 40% of the fatalities occurred in underground mining are due to roof and rib falls (Oraee *et al.*, 2011). Since one of the leading reasons of accidents in mines is roof and rib falls, causes of this hazard need to be understood clearly. There are several reasons for roof and rib fall occurrence such as, natural and geological conditions and incorrect mine designs. In order to evaluate reasons for these occupational injuries and fatalities, one way is using a proper risk assessment method.

In this chapter, general concept of occupational health and safety is presented starting from its development phase, and then structure of roof and rib falls in underground mines are described, including the factors that cause this kind of accidents. Then, a brief information about risk assessment and some risk assessment methodologies are presented. In the last section, Fault Tree Analysis (FTA) technique, as one of the risk assessment methods, and some application of FTA in occupational health and safety are described.

2.2 Occupational Health and Safety (OHS) Concepts

Occupational health and safety is one of the most important social aspects in the global world. Almost all countries have occupational health and safety regulations, and the common issue in those regulations is firstly the obligation of the employer to sustain a safe and healthy environment at work. In order to sustain a safe and healthy working environment, specification of the concept need to be well understood.

First step to develop a safe working environment is to understand some basic phenomena like hazard and risk. The concept of hazard has been defined by many organizations and scientists. According to World Health Organization (WHO), hazard is "*A possible threat of the source of exposure to injury, harm or loss, e.g. conflict, natural phenomena*" (WHO, 2001). In OHSAS 18001 (2007), hazard is defined as "*a source, activity or situation which causes injury or illness of a person*". In Turkey, hazard is defined in the Occupational Health and Safety Act No. 6331 as "*a potential of damage for loss which affects the employee or workplace which exists or may come from outside of the workplace*" (MoLSS, 2012a).

Another important phenomenon of OHS literature is risk. In OHSAS 18001 (2007), risk is defined as "*the combination of probabilities and consequences of hazardous situations or exposures*". In 2001, WHO defined risk as "*the probability of a result to be negative or factor that reveals that possibility*" (WHO, 2001). In Occupational Health and Safety Act No. 6331 risk is defined as "*the probability of loss, injury or other harmful consequences resulted from a hazard*" (MoLSS, 2012a). Risk is quantified in terms of likelihoods (probabilities) and consequences, in other words risk is defined in the literature as the multiplication of probability of an occurrence with the consequence of the occurrence.

2.2.1 Historical Development of OHS

Like all disciplines, occupational health and safety also has its own development period. The first advances in occupational health and safety started in Britain in the 17th century. Bernardino Ramazzini (1633-1714) is considered as a founder of occupational health and safety. Ramazzini made observations about hazards and risk that workers face up to in workplaces and preventive measures to those risks. He had also studied about ergonomics and work-worker adaptation and related diseases with occupations and was the first scientist that asks patients' occupations during medical examinations. Then, Robert Owen (1771-1858) pioneered the law of Health and Morale of Apprentices in Britain in 1802 which reduced working time to 10 hours. In 1833 in Britain, with the Factory Acts, inspectors had authorization to assign a doctor for medical examination before work starts. One of the most important developments was Roben's Report in 1972 in Britain. This report was based on an investigation about health and safety at work. In this report issues like safety laws and deficiencies in the designation of the health and safety hazards in workplaces were criticized. It was also mentioned that, human factor and working conditions like relationships between employee and employer and OHS responsibilities of employers should be included in the OHS perspective (Browne, 1973, Gunningham and Johnstone, 1999). Roben's Report also affected many countries besides Britain, such as, Sweden, Norway, Australia, and New Zealand. Also ILO Convention 176 Safety and Health in Mines (1995) was influenced by Roben's Report (Hermanus, 2007).

Other than these developments, Heinrich (1931), Peterson (1978), Weaver (1971), Bird and Loftus (1974), Wiegmann and Shappell (1997), and Reason (2000) improved occupational health and safety with developing accident causation theories through time. The most important theories are Heinrich's Domino Theorem, Reason's Swiss Cheese Model, and Wiegmann and Shappell's Human Factors Analysis and Classification System (HFACS).

Heinrich presumed that unsafe acts constitute 88% of the accidents, unsafe conditions constitute 10% of the accidents, and other 2% of the accidents are due to natural disasters and unpreventable situations (Heinrich, 1980). He presented the Domino Theory based on five serial factors; social environment and ancestry, fault of person, unsafe act, accident, and injury (Hosseinian and Torghabeh, 2012). Heinrich stated that "t*he occurrence of an injury invariably results from a complicated sequence of factors, the last one of which being the accident itself*." (HSE, 2015). This theory represents that each factors effect each other one by one and if there is not any preventive measures against these factors, an accident and/or injury will occur.

Another most important theory is Swiss Cheese Model by James Reason (2000). According to this theory, there are several factors that can lead to an accident and there are some defensive barriers in order to prevent these accidents. However, these barriers are not always perfect and may have some weaknesses. In order to describe this, in this theorem, Reason defines each cause as cavities in the layers of a Swiss cheese, these causes are organizational failures and supervisory failures, unsafe conditions and unsafe acts, and weaknesses of protective barriers are also shown as cavities of Swiss cheese layers. These barriers can be warning systems, automatic safety devices, trainings, monitoring, and control. Sequential occurrence of these layers cause the accident if they cannot be protected by barriers (Hosseinian and Torghabeh, 2012).

For human behavior and human error analysis, HFACS method is generally used. HFACS defines human error at four levels; (i) unsafe acts; which is divided into two groups as errors and violations. Errors are classified as decision errors, skill-based errors, and perceptual errors. (ii) prerequisite of these unsafe acts, this level contains the conditions of operators, environmental factors, and personnel factors. (iii) unsafe management, and (iv) organizational effects. With this method, reasons of the error was tried to be identified rather than finding out what an operator did wrong in order to understand the errors as outcomes of system failures or results of inherent systematic problems (Patterson and Shappell, 2010).

2.2.2 Occupational Health and Safety in World

Occupational accidents and injuries is an important problem throughout the world. For example in Europe, approximately 4,300 fatal occupational accidents and 3,500,000 non-fatal accidents occurred between 2008 and 2013 (European Commission, 2015). In the U.S.A., 4,585 fatal work injuries were reported in 2013. Annually there were approximately 5,650 fatalities occurred from 1992 to 2013 (OSHA, 2015).

In order to regulate the rules in workplaces with the intention of reducing work-related incidents, to keep the statistics of occupational injuries and fatalities, and to improve working conditions, some governmental-based and international organizations have been established. The most important international organizations related to OHS are ILO and WHO. Also, in the U.S.A., there are national organizations like National Institute of Occupational Safety and Health (NIOSH), Occupational Safety and Health Administration (OSHA), Centers for Disease Control and Prevention (CDC), and Mining Safety and Health Administration (MSHA). Other important occupational safety and health organizations are Safe Work Australia, Health and Safety Executive (HSE) of England, Canadian Centre for Occupational Health and Safety (CCOHS), and Work Safe BC of Australia.

In order to avoid occupational accidents, there is an 89/391/UE Directive for occupational health and safety in Europe. In the U.S.A., regulations are made according to Occupational Safety and Health Act of 1970 (OSH Act).

2.2.3 Occupational Health and Safety in Turkey

In Turkey occupational accident rate is on average 69,000 per year and fatality rate is 1,180 per year between the years 2008 and 2012 as presented in Table 2.1 (SGK, 2012).

Table 2.1 Occupational Accident and Fatality Statistics in Turkey (SGK, 2012)

Years	Occupational Accidents	Fatalities
2008	72,963	865
2009	64,316	1,171
2010	62,903	1,444
2011	69,227	1,700
2012	74,871	744

In Turkey, occupational health and safety regulations and legislations are conducted by the Ministry of Labor and Social Security – Directorate General of Occupational Health and Safety and Occupational Health and Safety Research and Development Institute (ISGUM), by the Ministry of Health, and by the Ministry of Energy and Natural Resources - Directorate General of Mining Operations. Occupational health and safety regulations are made according to the Occupational Health and Safety Law No 6331 and by regulations published according to that law such as, ‘Regulation of Occupational Health and Safety Risk Assessment in Workplaces’, ‘Regulation of Usage of Personal Protective Equipment in Workplaces’, and ‘Regulation of Occupational Health and Safety in Mining Workplaces’.

Sarı *et al*. (2001) conducted a study of an international comparison of Turkish coal mining industry safety performance both in lignite and hard coal production with USA, Poland, South Africa, Australia, British Columbia, and Canada in public and private sectors. Results are demonstrated for each million tons of coal production, thousand employees, and million man-hours of exposure. Each analysis showed that Turkish mining industry has one of the most adverse conditions by means of safety among the countries evaluated in that study (Sarı *et al.*, 2001).

According to SGK, in Turkey, there were 191,389 workers that had occupational injuries, and 14,186 of them were in the mining sector (SGK, 2012). In Table 2.2, occupational injuries and fatalities in Turkey mining sector from 2008 to 2012 are presented. According to that data, there were approximately 9,000 occupational injuries and 74 occupational fatalities occurred in mining sector per year between 2008 and 2012. Also there was a tragic mine accident occurred in a coal mine in Soma in 2014 ended up with 301 fatalities.

Table 2.2 Occupational Injuries and Fatalities in Mining Sector of Turkey (SGK, 2012)

Year	Injury	Permanent Incapacity	Fatality
2008	6,495	62	66
2009	9,056	40	20
2010	9,032	77	125
2011	10,507	128	116
2012	9,919	175	44

Another study conducted by Sarı *et al.* (2004) revealed the detailed analysis of accidents in two Turkish underground coal mines. The comparison of injury profiles is made between conventional and mechanized methods, and it was found that mechanized methods are more improved in safety and production. However, in mechanized panels there is an increase in haulage/transportation, machine and electricity related injuries. Also, it has found that manual handling related injuries in the mechanized panels were higher than in conventional panels. Besides most frequent accidents detected in conventional panels were falls of ground, struck by/falling object and handling material type of accidents. It was concluded that in order to decrease the accident and severity rates, a study should be performed to define the root causes of accidents in underground coal mines (Sarı *et al.*, 2004).

2.3 Roof and Rib Falls in Underground Mining

As it was mentioned earlier, roof and rib falls in underground mines are one of the most occurred accident types. There are several causes of roof and rib fall occurrence. According to the MSHA, roof and rib hazards occurred due to two major causes as natural sources and mining related sources. Natural sources vary from mine to mine, but generally these are local geology like type of the sedimentary rock, faults, ancient stream channels, slips, joints, kettle bottoms, horsebacks, fossils, thinly laminated or weak or brittle rocks. Also, local stress field and deep cover mining are other natural sources of roof and rib fall hazards. Mine-related sources can be listed as a wrong mine design, wrong support installation and removal procedures, poor roof bolt installation procedures, poor roof control plan, and poor mapping of geologic conditions (MSHA, 2008). There are also management and human-related sources such as, poor education and training, inexperience, poor roof and rib evaluations, not taking corrective actions instantly when an unsafe condition is observed, and going inby to abandoned regions (MSHA, 2008).

In order to control and prevent roof and rib falls, design and installation of support and reinforcement system should be able to resist static and dynamic loads. Visual examinations should always be conducted for roof, face and ribs, especially before start and finish the work. Loose materials should always be scaled with proper equipment and from a safe location. The roof control plan should always be followed and if any deficiency is detected, it should immediately be reported to a supervisor and it should always stay alert in case of a changing roof condition. Roof and rib conditions should be constantly monitored, especially; roof support unit indicators, geologic anomalies, floor heaving, and rib sloughing. It should be ensured that there is not any loose roof or rib near the working area, and workers should always stay away from the potentially hazardous areas (MSHA, 2008, Oraee *et al.*, 2011).

Sufficient ground control is the most important method in order to prevent roof and rib falls. Ground support installations are made to ensure the stability of the excavation and by this way minimize the risks of injury and fatality. Ground supports must be suitable to the geological conditions of the mine, stress conditions, and excavation geometry. Deteriorating ground conditions, inappropriate ground support, poor ground support installation, ground support that has deteriorated or corroded over time, and natural seismicity may result in rock falls (MOSHAB, 1999).

In order to have a sufficient ground support system, local scale of the mine should be properly known. Local scale of the mine is affected by local stress, by structural elements, and also by blasting damage to the rock mass (Hoek *et al.*, 1995).

In Turkey, in underground generally longwall mining method is used. An example of a typical support systems used in the faces are given in Figure 2.1. It is seen that generally used support type is timber support, which have been used since the first mining operations. After World War II, this support type is replaced with steel supports. Due to its properties, timber supports are widely utilized in underground mining. Advantages of timber supports are: due to its lightness it is easier to handle and construct, it has a high strength, its installation is simple and can be prepared in a short period of time, also they are slivered before broken thus provide time for replacement and reinforcement. Disadvantages of timber supports are: their mechanical resistance can vary greatly, they are sensitive to moisture that their mechanical properties reduce as the moisture increases, and also they are flammable (Labour Inspection Board, 2013).

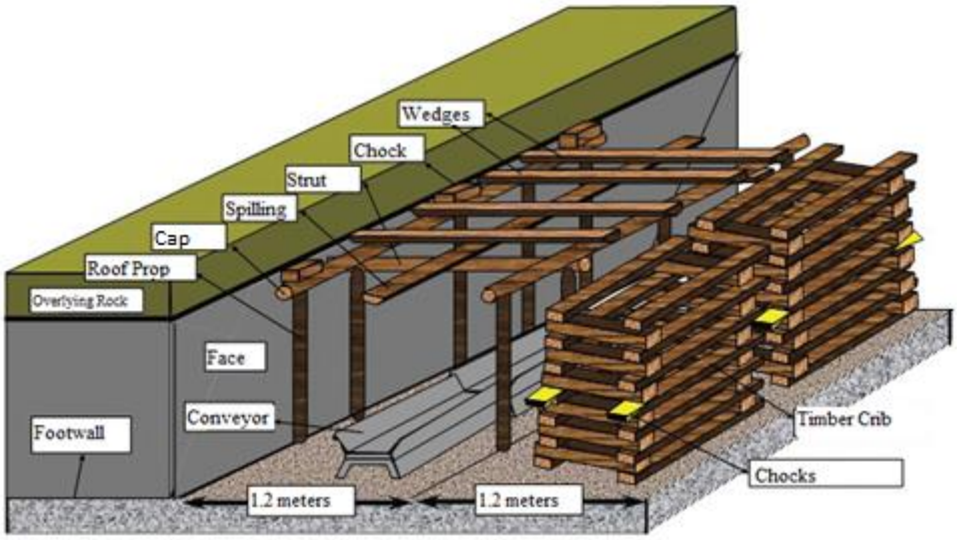


Figure 2.1 Perspective View of a Longwall Timber Support System (Labour Inspection Board, 2013)

On the other hand, steel supports have higher load carrying capacity, and they can be corrected several times after deformation. They are homogenous and less affected by natural conditions. However, steel supports have high initial investment costs. Also, their corrosion resistance is low and handling is harder relatively to timber supports (Labour Inspection Board, 2013).

Structure of the support systems in another concern. Cribs should be separate and roof pressure should be carried by the cribs that they should be well-tightened to the roof and be in align. Cribs should be installed after the floor cleans up. If there remains a lack above the crib after installation, it should be filled with timber material and pressured bags between the props of the cribs should be filled with pressured air in order to carry the load and pressure of the roof and floor. In the caving faces, while the cribs are removed, safety crib should be prepared before removing the crib. Before the installation of the permanent supports, temporary supports should be constructed in the faces. Especially in the rock fall areas, temporary supports should be constructed before working and safety of the region should be provided until the temporary supports constructed. Distance between temporary and permanent supports should not be more than 1.5 m (TTK, 2013).

Scaling bars and other materials designed to drop the loose rocks should be used from a safe distance in order not to danger the health and safety of the workers. Reinforcements should be conducted in the required regions and lack should be filled as soon as possible. Removal of the roof support should be conducted under the supervision of a supervisor. It is important to note that, temporary supports cannot be recovered. There should be at least two rows of temporary support between the workers and the unsupported region. Only people in charge could enter the dangerous regions where the zones are with potential roof and rib fall and insufficient support systems. A roof should be controlled and inspected regularly in order to avoid roof collapses. Also scaling and inspection must always be done to sustain the safety, to control the small, medium, and large rock falls in the faces and roadways. Especially scaling must be done after blasting operations. Scaffolds must be used in the higher faces. If there is an unfinished support work, it must be completed during the next shift. In the geologically important zones, like if there is a fault, specific support systems for these types of strata should be applied (TTK, 2013).

Another concern is the development and abandoned working zones. It is important to consider that the supports in the development workings could be insufficient though, inspections and controls for those supports should be made carefully in order to avoid roof collapses and rock falls. Also the development zones, ground water, faults, joints and other geological structures, planned excavations, and advances should all be gathered and written in the production map. If there are any fault zones or other geological structures, additional support should be installed and they should be continuously inspected. Check boring should be made at least 25 meters in the places which are known or suspected of groundwater. Entrance to the abandoned parts of the mines should be closed in order to prevent employee from entering. Instructions and characteristics of the support systems for every part of the mine should be well written and hanged to all related parts of the mine for the employee (TTK, 2013).

2.3.1 Engineering Studies about Roof and Rib Fall

Smith (1984) conducted a study in five different mine in Kentucky, the U.S.A., in order to determine the reasons of roof falls and ground conditions before the roof collapses occur in underground coal mines. In the study, roof conditions were evaluated with some selected parameters which are water and fracture existence before roof fall occurrences, rib sloughing, floor heave, support types as, mechanical anchor bolts or resins, period of roof falls after initial coal extraction, and distance to the coal face. In the study, it was found that there are two major causes of roof falls. The first one is stress conditions and the second one is geological disturbances like cracks, joints, presence of ground water, and slickenside. Also material of the roof, like whether if it is sandstone or shale, discontinuous bodies, presence of fractures, and steeply dipping coal beds affect the conditions of roof falls. As a conclusion, it was found that in the study area where roof falls mostly occur there was 88% water present before falls, and 71% of the falls occurred in less than 30 weeks after initial coal extraction, 75% of them has cracks in mine roof before roof falls occurred and 70% of the falls located usually far away from 30 m from the nearest coal face (Smith, 1984).

A method named Coal Mine Roof Rating (CMRR) developed by NIOSH scientists Mark and Molinda (1994) in order to define ground conditions of underground coal mines. CMRR method emphasizes on testing the rock material in order to define the strength of bedding plane even if the bedding planes are not visible. Data collection and calculations are made either using the information about roof falls and overcasts or using exploratory drill cores. Main parameters used during calculations are uniaxial compressive strength (UCS) of the intact rock, intensity of bedding and other discontinuities, shear strength, moisture sensitivity and the presence of a strong bed in the bolted interval. Also parameters like number of present layers, groundwater conditions and overlying weak beds are considered as secondary factors. Calculation is performed firstly by dividing the mine roof into structural units and then averaging all unit ratings of these divided units within the bolted interval using 'thickness-weighted average roof rating'. As a result of the calculations, a CMRR rating is found and according to the value of the CMRR safety factors (SF), bolt selection and bolt lengths are arranged (Mark and Molinda, 2005).

Bauer and Dolinar (1999) examined skin failures in underground coal mines in their study. Skin failures are described as failure of small blocks or slabs of roof and rib. Skin failures constitute a considerable safety hazard in underground coal mines. Injuries as a result of skin failures generally occur near faces, especially in the zones where the roof and ribs are unsupported. Skin falls are generally constituted by a combination of stress and geological discontinuities and they can be controlled by surface control systems rather than using sealants. Rib skin failures generally occur in thick coal seams. Some of the skin failure causes are sagging of strata due to the gravity, overburden pressure, which increases with depth, horizontal stress, and moisture or temperature sensitivity. Bauer and Dolinar (1999) also used CMRR method and stated that the lower the CMRR, the less competent the roof and it becomes more prone to skin falls. If a weak draw rock is present during coal extraction and if it is mined with the coal, there is a potential rib skin failure in the coal pillars (Bauer and Dolinar, 1999).

According to MSHA, approximately 50% of the fatal injuries under supported roof are caused by skin failures. When a roof and rib skin failure fatalities is compared, it is seen that rib failure fatalities are as twice as roof fall skin failure fatalities and they are caused by the lack of rib support which leads large slabs to spall from the ribs. Also, according to data gathered from MSHA, roof and rib fall incidents during 1995-1998, 57% of roof skin fall injuries occurred under permanent support and 35% of roof skin injuries occurred under temporary support or unsupported regions. Besides, 66% of the rib skin failure injuries occurred under permanent support and 15% occurred under temporarily supported or unsupported regions. Roof skins can be controlled by using wood planks, steel straps and channel, screens, or using the meshes like welded wire, chain link, or synthetic grid material. They can also be controlled using lots of gunite, mechanical or anchor bolts covering the roof with a synthetic grid material, or by spray coatings. Moreover the rib skin control can be made using sufficient bolts with the right length and in right locations also using posts or cribs that installed tightly near the ribs (Bauer and Dolinar, 1999).

Mines Occupational Safety and Health Advisory Board (1999) prepared a guideline which gives summarized steps of geotechnical risk assessment in Western Australia. Firstly, ground conditions should be classified according to whether it is soft or hard rock and also seismic conditions of the rock should be determined. Geotechnical properties of the rock mass should be quantified. Also it is important to determine the geotechnical properties according to rock mass classification methods and geology of the mine. Also, geotechnical properties should be analyzed according to underground surveillances, blast damages after large blasts, stress changes, groundwater and weakening of the rock mass through time. Making proper judgments according to experience through time and control the efficiency of scaling and drilling-blasting practices are another concern. Furthermore, the effect of the adjacent excavations and abutments need to be considered and rock supports and reinforcements should be determined accordingly (MOSHAB, 1999).

In another study conducted by Merwe *et al.* (2001) in South African Coal mines, causes of roof falls were investigated according to recorded 182 roof fall incidents. According to that examination, it was seen that fall types differ according to the thicknesses and the majority of the falls are skin falls which means the fall of thin layers. Roof falls were classified under three categories; skin falls, large falls, and major falls and every class has its own reasons for roof collapse. Major causes of roof falls were found as ineffective support and excessive spacing between bolts. Minor cases are found as burnt coal, dykes, bad mining practice, weathering, inferior materials and horizontal stress. Also, it was found that there were some other reasons for roof falls like, poor obedience to standards, poor support design, poor performance of support elements, and unknown nature of the stress regime (Merwe *et al.*, 2001).

According to a study conducted by Allanson (2002) while determining the hazards and risks for strata control; major failures were found as the improper type of support usage, the improper environmental condition assessment, inefficient or inadequate inspections, and wrong installation, failure in support equipment and insufficient skills and competencies of workers. According to these failures, some of the strata related hazards are; rib failure, workers under unsupported roof, undetected changes in strata conditions, skin failures, roof failures between supports, failure of supported ground, deficiencies in installation, wrong roadway alignment, and roof falls due to geological discontinuities (Allanson, 2002).

Iannacchione *et al.* (2007), also studied the methods for determining roof fall risks in underground mines using a qualitative risk assessment technique using a tool named roof fall risk index (RFRI) developed by NIOSH. This method is generally used for underground stone mines, but can also be adapted to underground coal mines. RFRI technique involves mapping of the roof fall hazards in underground and shows spatial distribution. Necessary information includes hazard maps, rock mass classification systems, and monitoring data. RFRI is applied firstly by evaluating risk by multiplication of the probability of a roof fall occurrence and consequence of a miner being injured by this roof fall. It is not possible to predict the size of a roof fall, thus it is presumed that roof falls always could seriously injure a worker. Roof fall probability of occurrence and consequences are classified in 3*3 risk matrix as low-medium-high and the results of risk are classified as low risk, moderate risk, and high risk. Miner exposure is found from frequency of an activity (in units of day, week, and month) versus the percentage of the workforce of that activity. Then, RFRI is calculated over regions in the underground mine by gathering RFRI values to appropriate roof fall probability categories that range from very unlikely to very likely. After evaluating the probabilities, underground mine is divided into sections according to RFRI values and spatially distributed according to risky zones (Iannacchione *et al*., 2005).

Shahriar *et al.* (2009) examined the roof falls in Iranian underground coal mines. The landslide risk assessment method by Einstein (1997) was used in order to determine the risks of roof falls in selected mines. Risk of roof falls was found using the likelihood of occurrence of the accidents and consequences. Then financial outcomes of the accidents were analyzed by means of injury, disability, fatality, equipment breakdown, stoppage in operation and cleanup, which should always be considered in determining preventive measures and costs of them. Then decision tree was conducted. As a result, proper education system, precise supervisory and support improvements were found as preliminary measures need to be improved in order to reduce roof falls (Shahriar *et al*., 2008).

2.4 Risk Assessment

In order to define hazards and risks for ground control, a proper risk assessment methodology should be conducted. Risk assessment is defined by Allanson (2002), as "*structured situational analysis of a particular interaction between equipment/people/environment to identify, quantify and prioritise risk against a predetermined standard and identify appropriate means of control*". Risk assessment requires various participants like administrators, designers, safety experts, and employees. However, main responsibility for occupational health and safety has always been on the employer. Details of these responsibilities generally differ in countries, but the general principle is always the same for every country's regulations. Risk assessment is one of the most important factors for sustaining safety and health in workplaces. General advantages of risk assessment can be summarized as, less accidents occur in workplaces because it provides to determine the factors systematically which leads to accidents and eliminate them (Özkılıç, 2014).

Risks management aims to reduce the risks of exposures to hazards in workplaces. It is a decision making process and a combination of the consequences of accidents with the probability of exposure to risk. Risk management starts with identifying hazards, their effects, workers exposed to that hazard, and exposed areas. Then continues with measuring exposures, analyzing present control measures, analyzing potential risks in terms of health and safety, prioritizing risks and finally with developing a control plan. A flowchart that explains risk management procedure step by step is presented in Figure 2.3 (Oraee *et al.*, 2011).

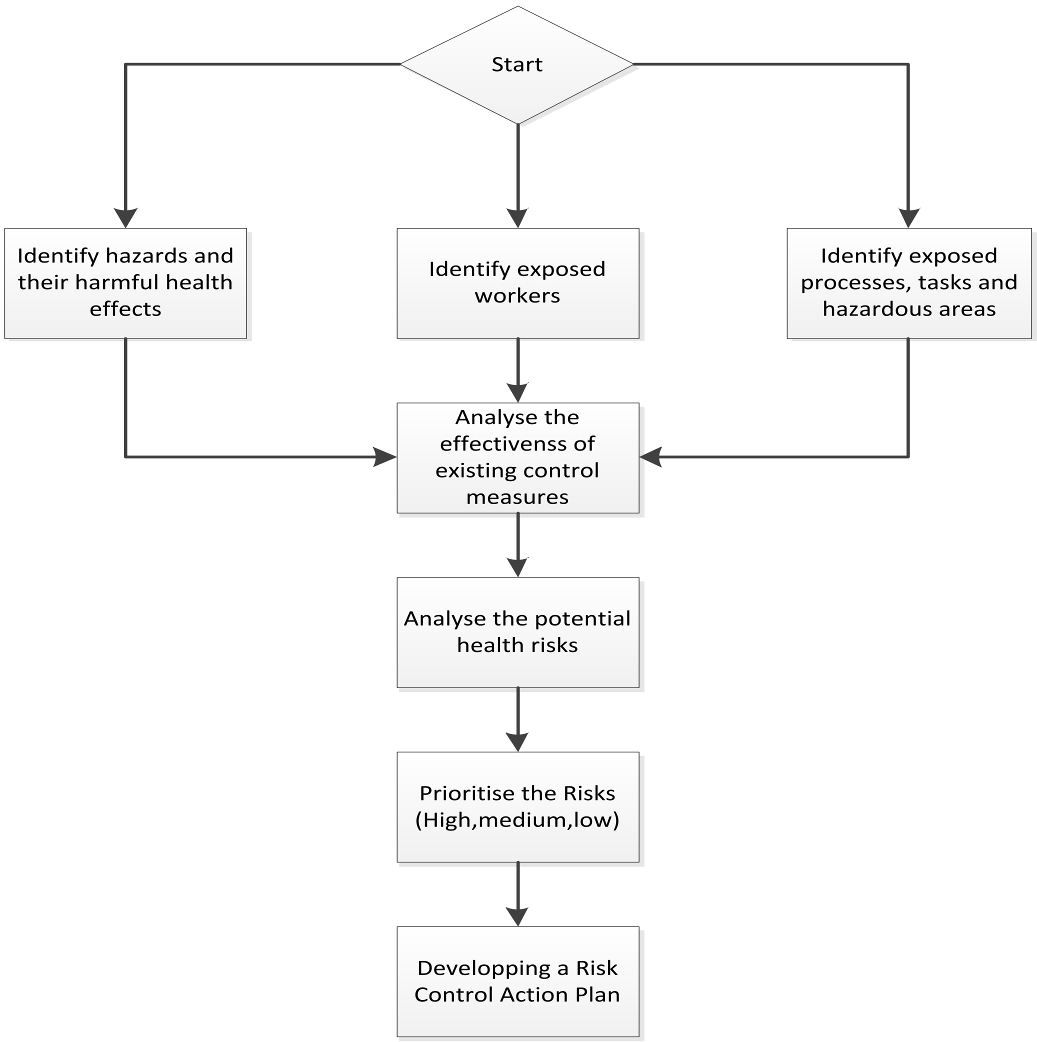


Figure 2.2 Risk Management Flowchart (Oraee *et al.*, 2011)

Parker *et al.* (2006) conducted a research on safety culture and made a classification of five topics on safety behaviors' and culture of organizations. These are pathological, reactive, calculative, proactive, and generative approaches. The pathological behavior approach has a safety understanding of 'Who cares about safety as long as we are not caught?', the reactive approach states that 'Safety is important: we do a lot every time we have an accident.', the calculative approach has an understanding of 'We have systems in place to manage all hazards.', the proactive behavior approaches to safety as 'We try to anticipate safety problems before.' and the generative behavioral approach states that ‘OSH is how we do business round here’ (Hecker and Goldenhar, 2014).

In Turkey, Risk Assessment has become obligatory according to the Occupational Health and Safety Act No. 6331. In Article 4 of this law it is stated that employers must make or delegate the risk assessment in workplaces. Risk analysis is defined in the same law as the necessary working in order to identify the internal and external hazards in the workplace, the factors that can lead these hazards to turn into risks and graduating the risks by analyzing the originated hazards and the studies that need to be done to determine the control measurements. According to Risk Assessment Regulation, risk assessment is defined as, ‘for all of the workplaces, starting from design state or organization, defining the hazards, specification and analysis of the risks, determination of the risk control measurements, documentation, updating the work done and renovation when it is necessary’.

2.4.1 Risk Assessment Methods

In all types of engineering or evaluation of complex systems, risk assessment takes part as a safety or reliability engineering. Defense industry and space studies pioneered the risk assessment studies. Especially studies increased as scientists began to ask various questions about occurrence mechanisms of serious accidents. In 1979, N. Rasmussen and his team made the first risk assessment for nuclear plants. That research was carried out based on the Fault Tree method. A methodology introduced by Rasmussen contributed safety research on nuclear plants (Özkılıç, 2014). In accordance with these studies and investigations, there were qualitative and quantitative risk assessment methodologies formed. Some of these methods are (Rasche, 2001):

- What if,
- Failure Mode And Effect Analysis (FMEA),
- Fault Tree Analysis (FTA),

- Hazard And Operability Analysis (HAZOP),
- Human Error Analysis (HEA),
- Preliminary Hazards Analysis (PHA),
- Failure Mode and Effect Analysis (FMEA),
- Failure Mode Effect and Criticality Analysis (FMECA),
- Fault Hazard Analysis (FHA), and
- Event Tree Analysis.

There are two analytical approaches by means of risk analysis methods as inductive and deductive approaches. Inductive approaches represent analysis of specific causes to general conclusions. It means that if the system concerns of a definite fault's effect to the general operation of the system, then it is an inductive method. PHA, FMEA, FMECA, FHA, and ETA are some examples to risk assessments with inductive methodology. Deductive approach is on the other hand, represents an analysis from general to particular. In this approach main aim is to find the reasons which lead system to fail. This approach is referred as "Sherlock Holmesian" in the Fault Tree Handbook and explained as facing with a given evidence helps to rebuild the events which prologs to crime. Accident investigations are typical examples of a deductive approach. An example of risk assessment methodology of deductive approach can be given as Fault Tree Analysis (FTA) (Vesely *et al*., 1981).

2.5 Fault Tree Analysis (FTA)

The Fault Tree Analysis (FTA) method was first developed in 1961 by H. Watson of Bell Telephone Laboratories of the U.S.A. Air Force for the evaluation of the Minuteman Launch Control System. Then this method was used by D. Haasl of Boeing Company as a significant system safety analysis tool in 1963. Then FTA method was adopted by the aerospace industry by means of aircraft and weapons. After aerospace industry, nuclear power industry also started to apply this method and use of this method in the nuclear power industry lead the most contribution than any other industries in development of FTA. Then from 1980s, FTA method was started to be used in safety community by the chemical industry, the automobile industry, rail transportation and also by robotics and software industries. From 1990s until the present, FTA has been used in almost all sectors and mainly in the safety sector by means of accident investigations (Ericson, 1999).

There are eight main steps in analyzing fault tree (FT) as presented in Figure 2.4 (Stamatelatos and Caraballo, 2002).

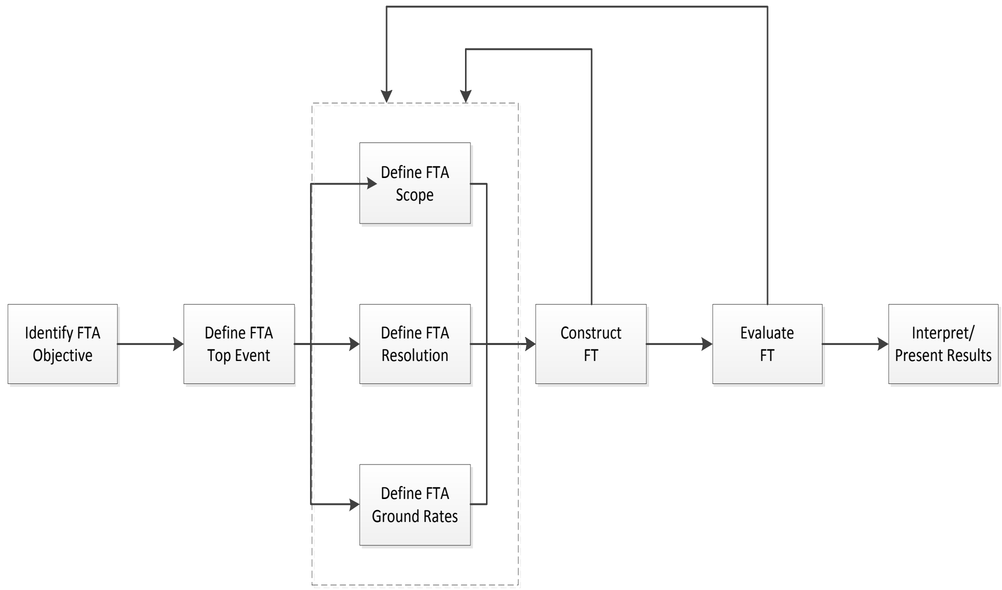


Figure 2.3 Fault Tree Analysis Formation Stages (Stamatelatos and Caraballo, 2002)

FTA is a deductive risk assessment approach. In deductive analysis, the system is conducting from general to the specific, which the system has already failed and the analyzer is aimed to find the events or components that lead this system to fail. Accident investigations are deductive analysis and FTA is used generally for investigations of accidents in order to find the basic causes of the accidents. In other words, in FTA method, a failed state of the system is specified and sequence of more basic faults contributing to this undesired event is constituted in a systematical way (Vesely *et al.*, 1981). Ericson (1999) defined FTA as "*the translation of the failure* *behavior of a physical system into a visual diagram and logic model*". The diagram is the tree that is constructed while finding the causes that leads the top undesired event. Constructed with the tree, it is easier to see the relationships between the causes and to define the basic events which are the root causes (Ericson, 1999).

FTA is both a qualitative and a quantitative model. It is a qualitative model which is assessed quantitatively. Quantitative approach of FTA based on probability theory and Boolean algebra. Fault tree construction and evaluation is a simple process when the tree is simple, but with large and complex trees, it becomes very difficult to solve and evaluate fault trees. Capability of solving a fault tree depends on to size, complexity, and computational capability (Ericson, 1999).

2.5.1 Implementations of FTA

In order to start a fault tree analysis, firstly an undesired event, which is the top event of the fault tree, need to be examined clearly. In determination of the top event, the current situation should be well understood since it affects the success of the analysis. After the top event is determined, failures that composed this top event should be evaluated. These failures are called 'primary events', and there are five kinds of primary events and distributions and explanations of each event is presented in Table 2.3.

Connections between top event and other events are made by gates. Gates show the relationship between output and input events. Basically, there are two main gates; the OR-gate and the AND-gate. The other gates are specialized version of these two main gates. Gate symbols of the FTA and their descriptions are given in Table 2.4

Table 2.3 Primary Event Symbols of FTA (Stamatelatos and Caraballo, 2002)

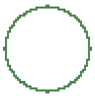
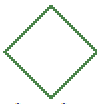
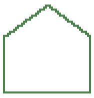
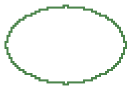
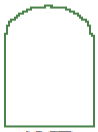
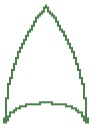
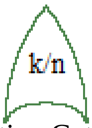
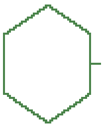
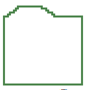
Event Type	Description
 Basic Event	The circle describes a basic initiating fault event that requires no further development. In other words, the circle signifies that the appropriate limit of resolution has been reached.
 Undeveloped Event	The diamond describes a specific fault event that is not further developed, either because the event is of insufficient consequence or because information relevant to the event is unavailable.
 House Event	The house is used to signify an event that is normally expected to occur. The house symbol displays events that are not of themselves faults.
 Conditional Event	The ellipse is used to record any conditions or restrictions that apply to any logic gate. It is used primarily with the INHIBIT and PRIORITY AND-gates.
 Intermediate Event	A fault event that occurs because of one or more antecedent causes acting through logic gates.

Table 2.4 Gate Symbols of FTA (Stamatelatos & Caraballo, 2002)

Gate Name	Description
 AND Gate	The output event occurs, if all of the input events occur. This means that system only fails if all components of the gate fail.
 OR Gate	The output event occurs if at least one of the input events occurs. This means that system will fail if any of the components fail.
 Voting Gate	The output event occurs if or more of the input events occur. This means that the system fails if any k-out-of-n components fail.
 Inhibit Gate	The output event occurs if all input events occur and an additional conditional event occurs. It is an AND gate with an additional event.
 Transfer Gate (Subdiagram)	Transfer in/out gates is used to indicate a transfer/continuation of one fault tree to another. In classical fault trees, the transfer gate is generally used to signify the continuation of a tree on a separate sheet.

A fault tree can be evaluated as a qualitative representation of Boolean relationships. In other words, a fault tree can be interpreted to an entirely equivalent set of Boolean equations so that a qualitative and quantitative characteristics of a fault tree could be obtained from Boolean equations (Stamatelatos and Caraballo, 2002). In Boolean algebra, the OR-gate is equivalent to the Boolean symbol "+", and the AND-gate is equivalent to the Boolean symbol "•".

The main reason for using Boolean algebra equations while representing fault tree is determining the minimal cut sets. After the fault tree is constructed and the primary events are described in detail, cut sets can be obtained. Cut sets are the primary qualitative outcomes of the top event. Since the basic events are the tail ends of a fault tree, combinations of these basic events are cut sets, which lead the occurrence of the top event and their smallest combination called the minimal cut sets. Minimal cut sets denote all cases that the basic events cause the undesired top event. All of the basic events in the minimum cut set need to occur in order to top event to be occurring, in other words, if some basic event in a minimum cut set does not occur, then the top event will not occur (Stamatelatos and Caraballo, 2002). These are the qualitative results of the fault tree analysis. Quantitative results are obtained from the probability of occurrences of the basic events of these cut sets.

2.6 FTA Studies in Literature

There have been many studies and investigations conducted using FTA model since it was first developed in 1961. One of them was the Apollo 1 launch pad fire on January 27, 1967. For the investigation of this accident conducted by the Boeing Company, FTA was performed on the entire system. Another is the Three Mile Island nuclear power plant accident on March 28, 1979. WASH-1400 study was conducted to investigate this accident and FTA method was broadly applied in this study. Also the space shuttle Challenger accident, occurred on January 28, 1986, was investigated using FTA. In this investigation fault tree was used to estimate the safe designs of the main engines (Ericson, 1999).

D. Haasl developed a methodology and rules which can be found on the Fault Tree Handbook (Vesely *et al*., 1981). J.B. Fussell is another leading author in the fault tree analysis area, especially with his "Synthetic Tree Model – A Formal Methodology for Fault Tree Construction" article published in 1973 (Fussell, 1972). Also in 1974, top-down cut set algorithm named "MOCUS – Minimal Cut Sets Upward" was developed (Fussell and Vesely, 1972). Also Fussell *et al.* (1974) developed a computer-based

program MOCUS to obtain minimal cut sets (Fussell *et al*., 1974). R. Willie (1978) developed “Computer Aided Fault Tree Analysis Program (FTAP)” (Willie, 1978).
When the FTA studies in the recent past are examined, it is seen that there are various studies made in the accident investigation field. Chi *et al.* (2014) made a graphical FTA in the construction industry in order to determine the reasons for fatal falls in the construction sector. In this study, a new perspective of fault tree was applied by showing the faults in graphical forms, sub reasons of fatalities in the construction sector were classified under three categories as unsafe behavior, unsafe machines and tools, and unsafe environment. According to 411 fatalities between 2001-2005 frequencies of experience, falling height, falling site, gender, age, company size was found. After that fatal accidents classified as single cause, 2-single cause, and 3-single cause and fault tree constructed according to these causes. Minimal cut sets were formed using Boolean algebra. In the final fault tree the most important factor of fatalities was found to be as improper use of PPE which is followed by improper scaffolds and unsafe climbing. Then a graphical representation of fault tree was formed due to the fact that pictures and graphical representations work well in communication and increasing pictures of safety preventions the effectiveness and it is stated that by this way workers feel more engaged (Chi *et al*., 2014). An important issue about this article is defining some causes of fatalities with single causes. It is important in accident causation that there is not a single cause for an occurrence of an accident, but instead accidents occur with two or more causes (or situations) coming together at the same time. Because of that, instead of defining some of the accidents with a single cause, authors should evaluate the causes in more detail and find the causes behind these single causes would be better.

In tunneling sector, a risk analysis of shield tunnel boring machine (TBM) tunnels using semi-quantitative FTA and the analytic hierarchy process (AHP) was conducted by Hyun *et al.* (2015). This study analyzes the risk generated by TBM. Four possible risks were found in the study: cutter-related malfunction, machine blockage or hold-up, mucking problems that hinder transporting excavated materials, and segment defects. While analyzing these risks, 3 sub-causes are found; geological factors, design factors and construction/management factors. Fault tree is constructed with 17 basic events, 4 primary events which are those four possible risks, and 10 secondary events. Data is gathered from a survey conducted with experienced TBM experts. Then risk impact analysis with analytic hierarchy process (AHP) applied according to the quantitative analysis of the FTA. After the probabilities of 17 basic events are calculated according to surveys, their probability scores are defined. Then, a relative importance matrix is formed. According to that matrix, risk impacts of each event are calculated using Eigenvector method and risk impact rating table is formed. All of this information is used to constitute the 5x5 risk scoring matrix of probability and risk impact. As a conclusion, events that need to be prevented first are found as incapability of mucking and segment damage (Hyun *et al.*, 2015). This study applied a different way of quantitative analysis with AHP. This study shows that FTA can also be used as a tool and can be used with other risk assessment methodologies. An important feature of FTA is that, it is one of the best tools to generate the root causes of accidents so that, in the study that Hyun *et al.* (2015) conducted, FTA is used to define the basic causes of TBM failures.

In the study conducted for a transportation system in Germany, a train collapse was examined using formal FTA, which was claimed to be the first complete formal FTA for an infinite state system. The formal fault tree was used to demonstrate if the failures are critical for the whole system to be failed or not. Top event of the FTA is a train passing a crossing on the railway while the bars are open. The result of the study showed that the collision was due to, brake failure, sensor fault, wrong position of the signals, short breaking time, and train being in a wrong spot (Ortmeier and Schellhorn, 2007). Understandings obtained from that study is firstly, formal FTA is a time-consuming procedure, proper generalizations need to be found and these generalizations usually cannot be found automatically, instead experts need to find them manually with human relations and ability. Even if the generalizations take a lot of time to be found, they provide a great advantage for experts.

Another FTA application was implemented to characterize the system's affection when there is not any reliability data are present. This system applies fault tree by estimating the failure rate of occurrence (ROCOF) (Curcurù *et al.*, 2013). This method's difference from the traditional FTA is that it differentiates basic events into two categories namely initiators and enablers. Initiators represent constituent failures and process parameter deviations regarding to normal operating conditions, while enablers represent failure of safety barriers to be activated. The advantage of this method is if the reliability data are inadequate, basic events can be indicated by existing sources of information which are formed by experts.

Ruilin and Lowndes (2010) conducted a FTA study for the underground coal mining sector. Firstly qualitative FTA was formed for a top event coal and gas outburst. Intermediate events that caused coal and gas outburst was found as gas properties of coal seam, physical and mechanical properties of coal seam, and geological conditions that create in situ vertical and lateral stress of the coal seam, and these primary events should all occurred in order to coal and gas outburst occurred in the area. Artificial Neural Network (ANN) algorithm was used for quantitative analysis. Firstly, the case study is done and showed that, in that region, only 13 of the 24 basic events have an influence on gas and coal outburst occurrence. Minimum cut sets of these 13 basic events were found using Boolean algebra. Also probability of occurrences of these 13 basic events was calculated. Eight basic parameters were determined to be gathered to use as inputs of the back-propagation (BP) solution algorithm, which was used to solve the ANN model. As a result of the BP algorithm, risk levels of these eight parameters were found and these risk levels used as input variables of the ANN model. As a result, in a comparative analysis of coupled FTA and ANN methods, 87% success was achieved (Ruilin and Lowndes, 2010). In this study it is seen that, since the mining environment and conditions are hard to evaluate, a quantitative analysis application is also hard to apply. In order to make efficient quantitative analysis, new approaches could be developed specifically for mining conditions. Also, all the conditions found in qualitative analysis are not always available for every condition and since, quantitative analysis can be made with less number of events.

A study in the mining sector was conducted by Zhang *et al.* (2014) for investigation of haul truck-related fatal accidents in surface coal mining using FTA. This study was conducted only qualitatively and analyzed 12 occurred accidents in West Virginia, the U.S.A. during 1995-2011. FTA was applied for all of the twelve fatal accidents in order to find the general root causes of haul truck accidents. Then the minimal cut sets are found according to that qualitative fault tree. Also, frequencies of seat belt usage, slope grades at the accident sites, distribution of each accident location, truck activity during accidents, weather conditions and characteristics of haul and access roads and dump site, and also which law violation of each accident takes place includes in this study. As a result of the study there was 18 root causes found for 12 accidents and the most common root causes were found as inadequate or improper pre-operational check, poor maintenance, and inadequate training (Zhang *et al*., 2014). This study evaluated qualitatively since there was not any probability calculations applied. Quantitative analyses are more complex to analyze, and in order to define the exact causes, quantitative analyses are necessary. In conditions of a presence of valid data, this study should be conducted quantitatively.

Beamish *et al*. (2010) conducted a research study on analyzing the root causes of spontaneous combustion in coal mines using FTA. In this study FTA was formed by nine experienced people who are experts in their own fields. In order to define root causes, after evaluating the top event, coal spontaneous combustion, primary, secondary and intermediate events are developed. Primary causes were found to be; self-heating, less than adequate dissipation of heat, and less than an adequate monitoring system. Also, these three primary causes should be occurring at the same time in order the top event to occur thus they combined with an AND gate. Then other intermediate events are subdivided further until the basic events found. By this method, a Spontaneous Combustion Management Plan (SCMP) was implemented by finding the root causes with the FTA risk assessment tool (Beamish *et al*., 2010). FTA is formed on the basis of experts experience and opinions. Basic causes are specified according to experts' comments. Because of that, there is not a single fault tree for a top event. Although, each fault tree can show variations for the same top event according to experts' decisions. This study is important to show that FTA is a complex method and need to be implemented with comprehensive thinking with different experienced individuals who are experts in the study area.

Another study was conducted to investigate the reasons of roof fall accidents in underground coal mines for 146 roof fall accidents occurred during 1980 – 2000 using FTA with fuzzy theorem (Jiang *et al.,* 2012). While constructing the FTA, human unsafe behavior was also considered. With a top event of 'roof fall accidents', there are 5 intermediate and 28 basic events. Quantitative analysis was made using fuzzy approach. The triangular fuzzy number is used to calculate the probabilities of the basic events. There are not detailed data shared, but as conclusion five of the basic events are found to be the most important as a result of the weightiness of fuzzy probability. Five main causes of roof fall in underground coal mines are found to be in a decreasing importance are; large area of empty support, meeting geologic tectonic zone, long time of roof suspension, low safety consciousness and diathesis of leaders and workers, bad engineering quality (support system), and volatile command (Jiang *et al.*, 2012). This study does not include much information about the data, but only the application of the fuzzy theory. Also, the basic events found in the fault tree are not detailed as can be understood from main causes.

CHAPTER 3

DATA AND STUDY AREA

3.1 Research Area

According to the statistical data obtained from the International Energy Agency (2012), between the years of 2009 and 2011, Turkey was the 12th among the major coal producer countries and the 4th in the major lignite producer countries. However, it is not mentioned among the major hard coal producer countries (IEA, 2012). At the beginning of 1980s, 80% of the total hard coal consumption, and between 1980s and 1990s, 45% of the total hard coal consumption was provided by the national resources in Turkey. However, in 2010, only 9.8% of the hard coal consumption was provided by the nominal resources, which means there is a significant decrease in production rates (TTK, 2013).

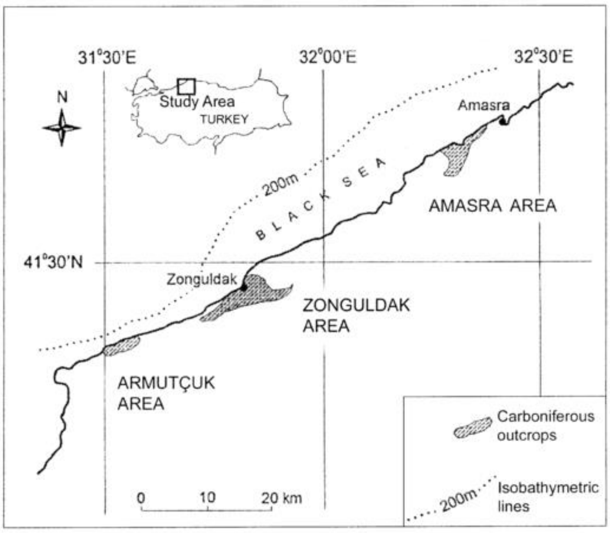


Figure 3.1 Zonguldak Coal Basin (Gürdal and Yalçın, 2001)

Zonguldak coal basin contains major bituminous coal deposits of Turkey and it is located in northwestern Turkey along the Black Sea, (Figure 3.1) (Gürdal and Yalçın, 2001). The basin has a complex geological structure which makes mechanized coal production almost impossible and requires labor-intensive conventional coal production methods. Coal production is conducted by Turkish Hard Coal Enterprises (TTK) in this region. TTK operates five mining sites in this region, namely: Amasra, Armutçuk, Karadon, Kozlu, and Üzülmez. TTK was first founded in Zonguldak in 1848. The company has its current name in 1983 with the decisions of the council of ministers. TTK had continued its operations in these abovementioned five regions since 1983. The calorific value of hard coal reserves in the basin varies between 6,200 and 7,200 kcal/kg (EURACOAL, 2013). Annual average productions of the company have been 2.7 million tons in the last 14 years.

This research is conducted in one of these regions, TTK Amasra coal field, due to the accessibility of the data and the suitability of the coal basin for the research. The first production activity in Amasra region was started in 1848. These activities had continued until 1940 by various private companies. The field was assigned to Ereğli Coal Enterprises (E.K.İ) in 1953 and the first mine site established by government funds began production in Tarlaağzı Village. The first opening up of drift was started in Demirci Stream in 1965, where the production activities still continue. After the region name changed several times, the establishment had its legal identity with September 24, 1997 dated and 16/192 numbered decision of the board of management of TTK as “Amasra Hard Coal Institution” in January 01, 1998 (TTK, 2013).

Production activities are conducted in the Amasra coal field in a 49 km^2 area. The area is surrounded by Tarlaağzı Village in the West; Abas, Saraydüzü, and Karainler Villages in the East; Black Sea in the North; and Bartın in the South. Establishment conducts production and development activities down to -400 m depth in a 13.5 km^2 area which is known as resource area A in the North of the 49 km^2 area (Figure 3.2). The rest of the area is operated by several private subcontractor companies (TTK, 2013).

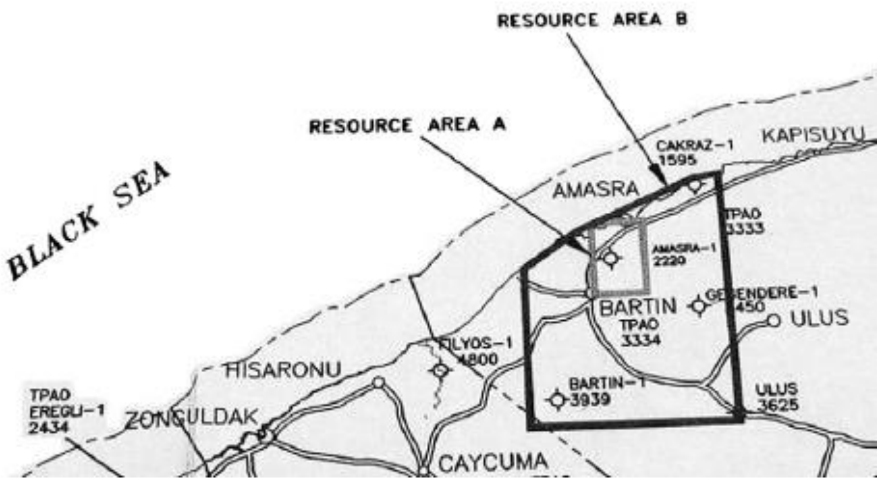


Figure 3.2 Amasra Hard Coal Production Area (TTK, 2013)

The reserves of the TTK Amasra coal field in 2014 were stated to be 406,565,772 tons. Proved, probable, and possible reserve status in 2014 is given in Table 3.1. There is also present reserve is given in this table as 317,755 tons, which corresponds to the reserves that are currently produced (TTK, 2014).

Table 3.1 Reserve Status of Amasra Underground Coal Mine in 2014 (TTK, 2014)

Category	Level (m)	Total Reserve (tons)	%
Present Reserve	-	317,755	
Proved Reserve	-30/-550	169,661,017	42
Probable Reserve	-100/-550	115,052,000	28
Possible Reserve	550/-1200	121,535,000	30
Total		**406,565,772**	**100**

3.1.1 Production Method and Employment

In the coal production faces, generally the longwall caving method is applied. In the hazardous faces, retreating longwall caving method is applied and in the faces which have steeply dipping seams and convenient seam thickness production is made by drilling and blasting. More than 50% of the production is obtained by retreat longwall caving mining method in which timber supports are used for support system.

As of the year 2014, there were 688 employees at Amasra underground coal mine and 518 of these employees were working in underground and 137 of them were working in the surface operations. In the study area, there are three shifts per day and every shift duration is 6.5 hours. According to data gathered in April 2015 during the site visit, in the first shift (08:00-14:30) there are 254 employees, in the second shift (16:00-22:30) there are 144 employees, and in the third shift (00:00-06:30) there are 120 employees working underground. Moreover, there were 155 employees working as administrative staff.

3.2 Data Collection

Accident data from 2003 to 2013 are obtained from Occupational Health and Safety Management of TTK Amasra Hard Coal Institution. Allocation of accidents occurred in five mining sites according to year of experience and age are given in Table 3.2 and Table 3.3. Majority of these accidents occurred in Karadon, due to the large area of the site and high number of workers. In Table 3.2, it is seen that most of the injuries occurred in the first five years and as the experience increases there is a trend of decrease in injuries. Besides, most of the injuries occurred in 26-30 age group (Table 3.3). After age 30, as the age increases, there is also a decrease in injury rates.

Table 3.2 Total Accidents According to Experience in 2003 - 2013 (TTK, 2015)

Mine Site	0-5 Years	6-10 Years	11–15 Years	16–20 Years	21–25 Years	26–47 Years
Armutçuk	1,936	502	255	93	29	4
Amasra	1,290	601	334	102	33	5
Üzülmez	2,697	945	634	241	114	6
Karadon	8,475	1,885	1,051	509	155	22
Kozlu	3,237	896	489	259	78	4
Total	**17,634**	**4,828**	**2,763**	**1,203**	**408**	**40**

Table 3.3 Total Accidents According to Age in 2003 - 2013 (TTK, 2015)

Mine Sites	18-25	26-30	31-35	36-40	41-45	46-65
Armutçuk	373	1,159	872	264	119	30
Amasra	190	850	790	315	176	44
Üzülmez	365	1,702	1,470	700	305	95
Karadon	1,813	5,171	3,045	1,086	750	227
Kozlu	558	1,998	1,398	587	336	86
Total	**3,298**	**10,879**	**7,574**	**2,952**	**1,685**	**481**

Hazards and risks in the research area are evaluated by 5x5 matrix risk assessment method. In 5*5 matrix method, risk is measured by means of likelihood and impact (consequence). Measuring risk in this way gives a value for likelihood against impact and therefore risk can be measured with an easily comparable value (HSE, 2013). An example to some parts of this risk assessment is given in Table 3.4. These given examples are selected according to relevant parts with this study. From analyzing this risk assessment, it is seen that the risks are not evaluated efficiently and some hazards and risks are not mentioned in the analysis, and also detected hazards and risks are evaluated in the low risk level. Application of the present risk assessment in the company is considerably wrong. Risk assessment should be revised and all existing hazards and risks should be added and preventive measures to be taken should be written in detail in the analysis. This situation is further analyzed in detail in Chapter 4.

In the study area, before employees start working, they take an adaptation training program. This program begins with formation of coal and mining, safety and labor laws and continues with training of mine safety, support, transportation, mining safety, ventilation, electricity, and first aid and also practical trainings for 21 days. After the training program, all workers take the competence exam. Program of this adaptation training is given in Table 3.5. Inadequacies about procedural and occupational health and safety trainings are discussed in detail in Chapter 4.

Table 3.4 Some Representative Examples of Company's 5x5 Risk Assessment

				RISK			RISK REDUCTION				
Operation	**Task**	**Equipment Used**	**Hazards**	**Likelihood**	**Impact**	**Risk Level**	**Present Control Measures**	**Control Measures to be Taken**	Probability	Residual Risk	Risk Level
Inspections	Scaling	Various equipment	Roof collapse	5	1	5	Education, PPE, Periodic Inspections, Equipment control, Support Installation	?	1	5	Low
Support Installation	Manual transportation of timber material to faces	Timber support material	Limb injury	4	1	4	Education, PPE	?	1	4	Low
			Hand Injury	2	2	4	Education, PPE	?	2	4	Low
			Slip and fall	2	2	4	Floor cleaning	?	2	4	Low
Support Installation	Excavation for support installation	Pick hammer and mattock	Hand-Arm Injury	2	3	6	Education, PPE	Education, PPE	2	4	Low
			Face sloughing	5	2	10	Education, PPE	?	1	5	Low

Table 3.5 Underground Mining Adaptation Training Program in the Study Area

DAYS	HOUR	SUBJECT
1. Day	08:30 - 10:00	Meeting and Importance of the Course
	10:15 - 11:45	Formation of Coal
	13:30 - 15:00	Labor Law
2. Day	08:30 - 11:45	Mine Safety
	13:30 - 15:00	Labor Law
3. Day	08:30 – 11:45	Information about Supports
	13:30 - 15:00	Mine Safety
4. Day	All day	Information about Transportation and Haulage
5. Day	All day	Practical Training
6. Day	All day	Practical Training
7. Day	All day	Information about Mine Development
8. Day	08:30 - 11:45	Information about Electricity
	13:30 - 15:00	Information about Ventilation
9. Day	08:30 - 11:45	First Aid Training
	13:30 - 15:00	Information about Ventilation
10. Day	All day	Practical Training
11. Day	All day	Practical Training
12. Day	All day	Practical Training
13. Day	08:30 - 11:45	Information about Transportation and Haulage
	13:30 - 15:00	Mine Safety
14. Day	08:30 - 11:45	Information about Supports
	13:30 - 15:00	Mine Safety
15. Day	All day	Mine Safety
16. Day	08:30 - 11:45	First Aid Training
	13:30 - 15:00	Labor Law
17. Day	08:30 - 11:45	Information about Equipment
	13:30 - 15:00	Information about Electricity
18.-20. Day	All day	Practical Training
21. Day	All day	Exam

3.3 Occupational Accidents in Amasra Underground Coal Mine

In Amasra underground coal mine, totally 2,365 accidents occurred from 2003 to 2013. Accidents resulted in minor injuries, medium injuries, major injuries, and fatalities. There were four occupational fatalities occurred between the years 2003 and 2013 (Table 3.6). Two of these fatalities were caused by rock fall from the roof and other two occurred during transportation. Besides of these fatalities, there were 13 accidents resulted in major injuries and four of these injuries were caused by roof collapse and others are classified under miscellaneous and material usage.

Table 3.6 Occupational Fatalities in Amasra Underground Coal Mine during 2003 to 2013

Fatalities	Accident Date	Cause of Accident
1.	01.11.2004	Rock fall from roof
2.	01.11.2004	Rock fall from roof
3.	01.06.2012	Transportation
4.	26.11.2013	Transportation

Figure 3.3 graphically depicts the accidents in the Amasra coal field. When the graph is examined, it can be seen that there was a trend of decrease until 2008, and accidents had tended to increase between 2008 and 2012. Then accidents began to decrease again until 2012, and then started to increase. Reason for these increases could be due to the general recruitments in 2009 and 2012 in the company. There were totally 181 and 16 employees started to work in 2009 and 2012 respectively. As it can be seen from Table 3.2, accident rate is higher in the first five years of occupation.

In Figure 3.4, histogram of accidents per year with mean, median, and standard deviation of this accidents are presented. In this eleven years, there were totally 2,365 accidents. Mean of this data is found as 215 with a standard deviation of 52.38.

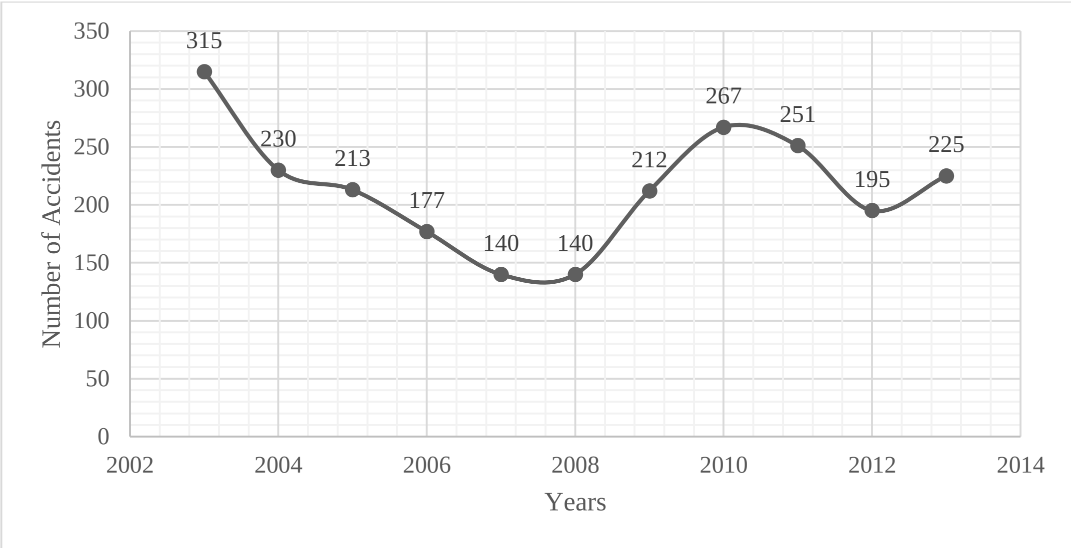


Figure 3.3 Distribution of Occupational Accidents in Amasra Coal Field

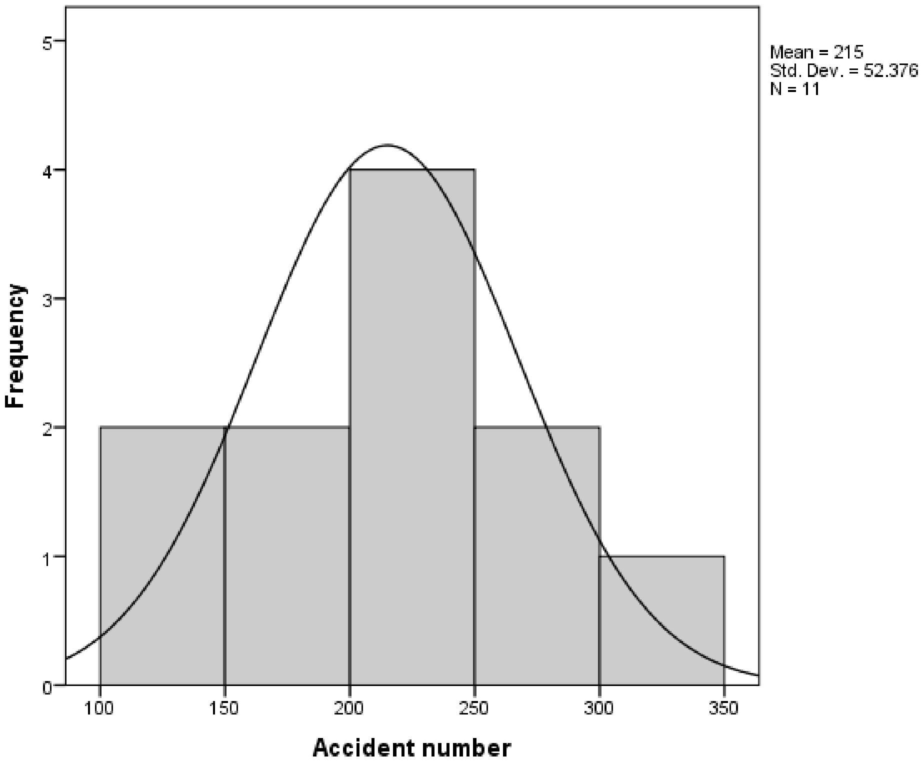


Figure 3.4 Histogram of Number of Accidents for 2003 – 2013

Accidents occurred in Amasra underground coal mine is classified under six main causes, namely; roof and rib falls, material, transportation, machinery and electricity, hazardous gasses, and miscellaneous. Number of the accidents with these main reasons is given in Table 3.3. Surface and underground operation accidents from 2003 to 2013 are all included in these data. According to Table 3.7, it can be seen that most of the classified accidents occurred due to roof and rib falls with 879 accidents (37%). Even if the number of miscellaneous accidents are higher than roof and rib fall accidents, miscellaneous accidents include the topics that could not be classified under a major cause like roof and rib fall or electricity, but instead it includes accidents due to slips and falls and other similar unclassified accidents. Because of that it cannot be classified as a main reason in the accident data.

Table 3.7 Number of Accidents and Lost Days According to the Causes of Accidents

Cause of Accidents	Number of Accidents	%	Lost Days
Roof and Rib Falls	879	37.17	10,299
Material Usage	390	16.49	1,924
Transportation	113	4.78	2,328
Machinery and Electricity	62	2.62	452
Hazardous Gasses	5	0.21	22
Miscellaneous	916	38.73	89,503

Also, during these 11 years (2003-2013), there were 104,528 lost days due to the accidents in the research area. There were 10,299 lost days due to roof and rib fall accidents as presented in Table 3.7.

From these 2,365 accidents occurred in Amasra underground coal mine, most affected body parts are found as hands and feet (Figure 3.5). The reason for this could be the insufficient personal protective equipment or employee’s unsafe behavior of not wearing the proper personal protective equipment. Reasons of these inadequacies about personal protective equipment are analyzed in detail in Chapter 4.

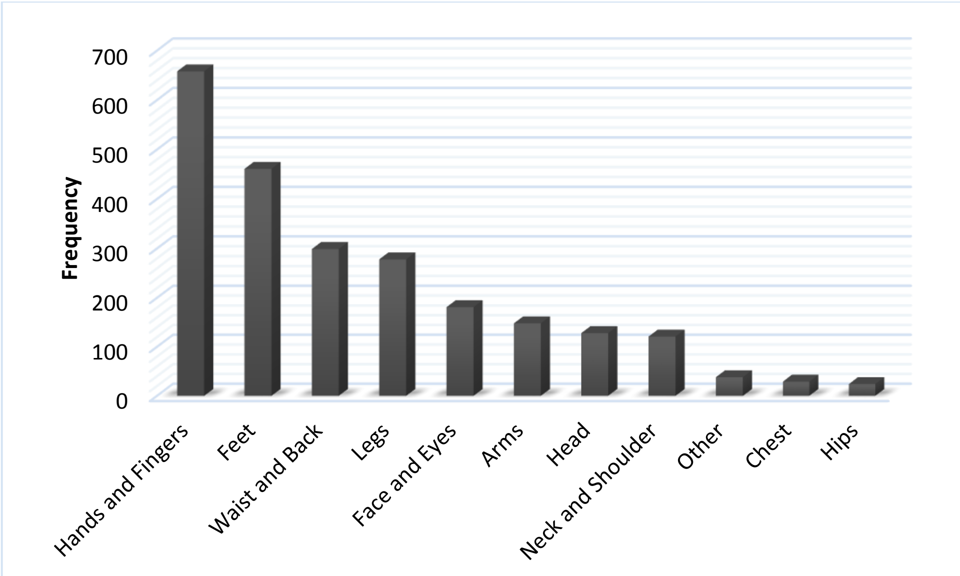


Figure 3.5 Distribution of Injured Body Parts

It is important to note that this classification of accident reasons is made by the company and gathered from the data sheets. Accidents that are classified as miscellaneous should be revised and studied in detail, since the causes of these accidents under this classification are not clearly stated.

3.3.1 Roof and Rib Fall Accidents in Amasra Underground Coal Mine

In TTK Amasra coal field, roof and rib falls constitute the majority of the classified accident causes in the research area with 879 accidents (37%). According to the accident data that gathered from the company, roof and rib fall accidents covered in the research occurred during coal excavation (27%), support installation and removal (46%), maintenance and repair (3%), scaling (3%), cleaning of coal and/or mine environment (9%), drilling and blasting (9%), and transportation (3%) operations as presented in Figure 3.6. Most of the roof and rib fall accidents occurred during support installation and removal and coal excavation operations. Roof and rib falls means falls of small, medium, and large rocks; and coal from roof and ribs, falls of loose rocks and coal from the face. Also, deterioration or distortion of ground strata is another factor of roof and rib fall injuries and fatalities. These data are analyzed further in detail and the root causes of these accidents are examined and analyzed in Chapter 4 using fault tree analysis.

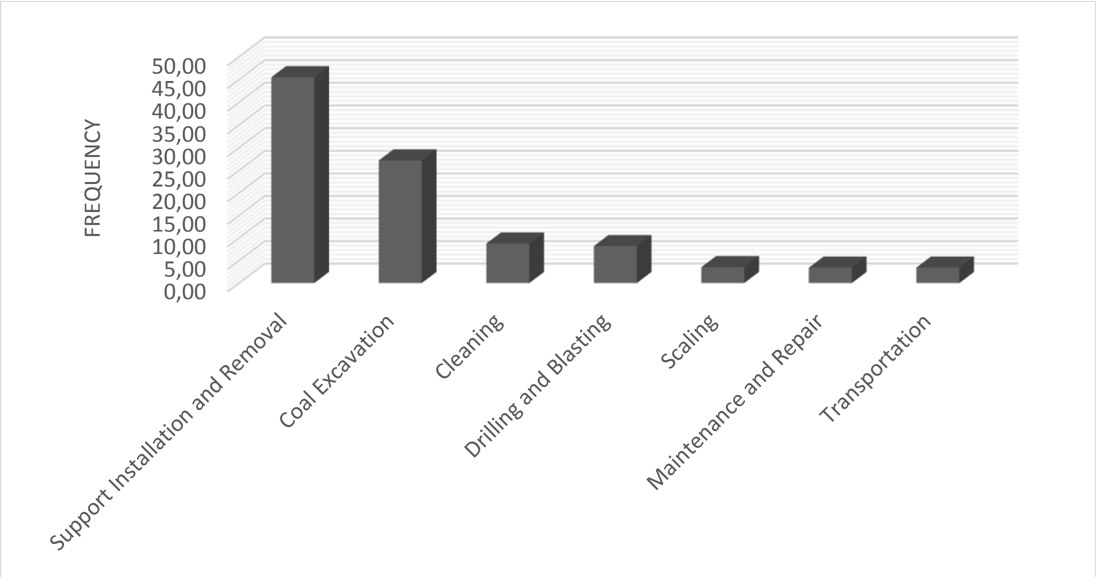


Figure 3.6 Operations during Roof and Rib Fall Accidents

In order to determine the most hazardous working branches by means of roof and rib fall hazards, each branch is analyzed and it is found that 729 of the 879 (83%) roof and rib fall accidents happened involving production workers. This shows that the production work is the most hazardous operation by means of roof and rib falls in the research area.

The further analysis of the workers involved in the accidents indicates that education levels of the workers in roof and rib fall injuries and fatalities should also be considered. From the accident data it was seen that:

- 73% of the workers have graduated from primary school,
- 18% have graduated from high school, and
- 9% have graduated from secondary school.

CHAPTER 4

QUALITATIVE AND QUANTITATIVE FAULT TREE ANALYSIS

4.1 General Information

In this study, injuries and fatalities occurred in an underground hard coal mine between 2003 and 2013 were examined. This examination was carried out using fault tree analysis (FTA) to identify the root causes of roof and rib fall accidents occurred in the study area. During the study, two site visits were carried out in 2014 and in 2015. During these site visits, it was investigated that there were some deficiencies about the support system. Also injury and fatality data between 2003 and 2013 were obtained from the company during these site visits. Preprocessing of data, which excludes incidents records, revealed that the majority of the accidents occurred due to roof and rib falls. Data are composed of injured individuals, the date of the incident, occupations of individuals, educational levels, a general name of the place of accident, type of the accident (roof/rib fall, electricity, transportation, *etc.*), consequences of accidents (injury, serious injury, fatality), affected part of the body, recovery time, and short description of the accident. Also, birth dates, age of recruitments, and detailed educational levels of workers, training program, and personal protective equipment lists were obtained from the company.

As it was mentioned in Chapter 3, two fatal accidents occurred due to roof and rib falls in the Amasra underground coal mine. There were totally 879 accidents, occurred due to the roof and rib falls which resulted in 10,299 days lost between 2003 and 2013. Among these 877 injuries, nearly 43% of workers have minor injuries, 56% have medium injuries and the rest are seriously injured or ended up with fatality according to the accident data of the establishment.

Based on this information, a qualitative and a quantitative FTA were applied in order to determine the reasons of roof and rib falls in the research area and to improve current control measures.

4.2 Qualitative Fault Tree Analysis

As it was explained comprehensively in Chapter 2, FTA can be made qualitatively or quantitatively. Initially, qualitative FTA was applied based on the deficiencies and inadequacies identified in the study area. These findings were then evaluated during the site visits carried out in August 2014 and April 2015. The top event of the fault tree is determined as 'Roof and Rib Fall Accidents in an Underground Hard Coal Mine'. There are three major events (Engineering/Supervisor, Management, and Human Errors), 16 intermediate events, and 39 basic events constituted. All major events, intermediate events and basic events with their frequency rates and percentages within the whole system are presented in detail in Table 4.2. Explanations and contents of each event are given in detail in the following sections.

Also, the fault tree of the system is given in Figure 4.1. Major events Engineering/Supervisor Error (A1), Management Error (A2), and Human Error (A3) are combined with Voting Gate (2/3) in the fault tree. It is important to note here that, every occupational accident occurs from various reasons that comes together to generate the accident. Thus, an injury or a fatality cannot be occurred from a single cause alone. Quite the contrary, incidents should occur due to two or more causes coming together. Because of this reason, gate to combine these three major events are chosen as Voting-Gate (2/3). This means that, in order to roof and rib fall accidents to take place, at least two of these three events must be occurring. The other events (B1-B8) are shown with sub-diagrams in the tree. Sub-diagrams indicate a continuation of the fault tree on a different page which will be explained in the following sections. Also, every accident is evaluated under different failure events, in other words, every cause is evaluated for each accident. Hence, the cumulative frequency is higher than the actual number of accidents.

According to the frequencies presented in Table 4.1, Management Error has the highest rate of accident frequency. It is followed by Engineering/Supervisor Error and Human Error in a descending order. Also the event that contributes most of the accidents is X18-Insufficient Risk Assessment with 10.97%, which is followed by X7 - Improper Additional Roof Supports (9.95%), and X10-Poor Safety Culture (9.26%). Events that do not have frequencies are shown in the fault tree as undeveloped events. Each failure event are described in detail in Section 4.2.

Also in the last column duration of sick leave for each event is given. This column represents the result of each accident that occurred to each worker separately by means of total sick leaves and since some of the accidents occurred at the same time, or different accidents occurred in the same days, result of some events are higher than the duration of eleven years period. The highest sick leave duration among these events again belongs to 'Insufficient Risk Assessment (X18)' with 10,299 days.

Between 2003 and 2013 there were totally 10,299 lost days according to the accident data of Amasra underground coal mine and according to data gathered from TTK among these years there were approximately 500 workers that have worked in underground per year. The severity percentages for each event are calculated according to Lost Days/10,299 days/Number of workers. Severity percentages of the events which can be calculated quantitatively are given in Table 4.2 in a descending order.

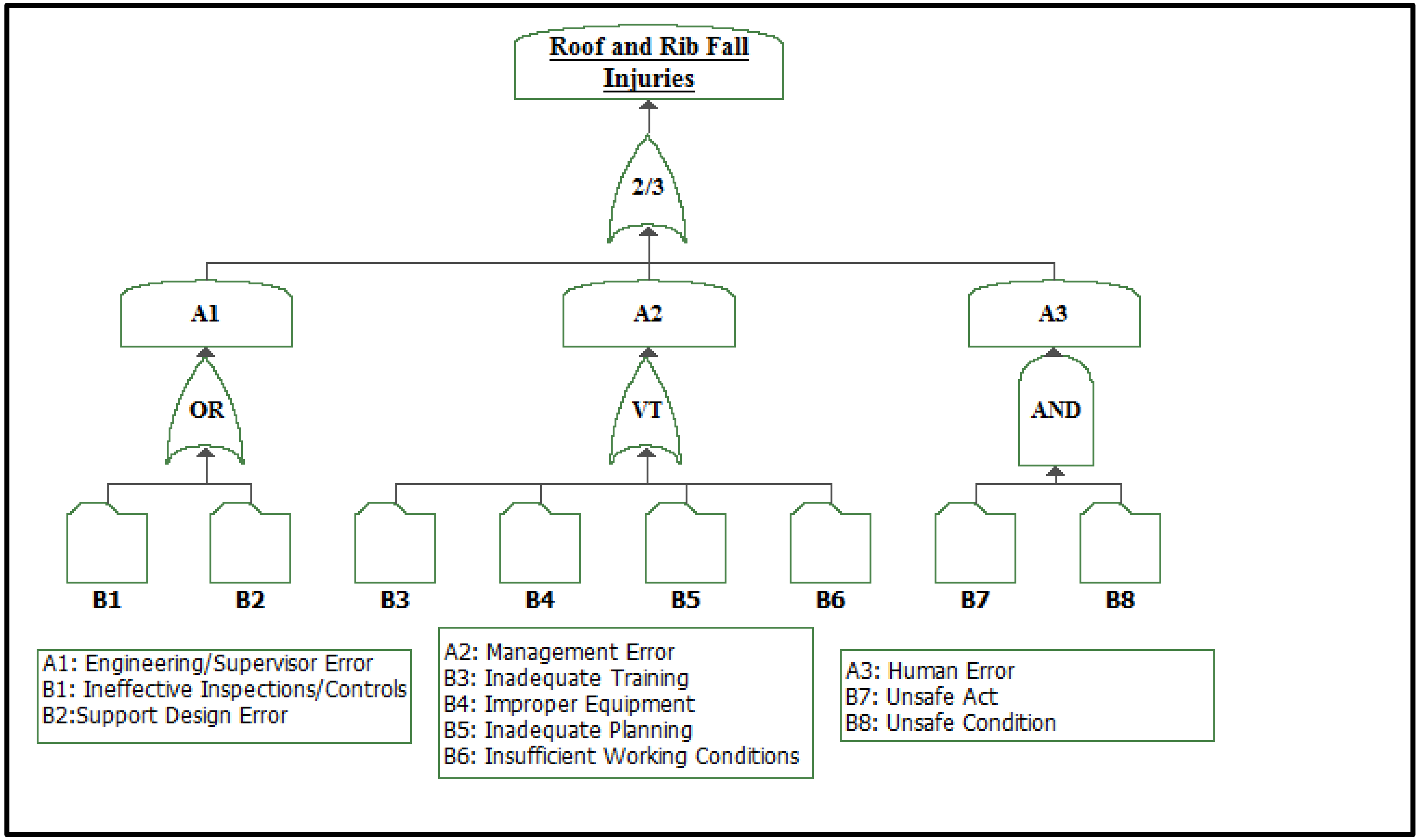


Figure 4.1. Fault Tree of Roof and Rib Fall Accidents in an Underground Hard Coal Mine

Table 4.1 All Failure Events and Frequencies in the FTA

Events	Frequency	%	Total Duration of Sick Leave (days)
Total	**8,012**	**100.00**	**-**
A1 - Engineering/Supervisor Error	**2,731**	**34.09**	**-**
B1 – Ineffective Inspections and Controls	**1,246**	**15.55**	**-**
X1 - Inefficient Scaling	355	4.43	4,592
X2 - Inefficient Support Inspections	271	3.38	3,103
X3 - Failure to Control Preventive Safety Measures	620	7.74	7,365
B2 – Support Design Error	**1,485**	**18.53**	**-**
X4 - Insufficient Roof Support	206	2.57	2,258
X5 - Deterioration or Distortion of Support Elements	13	0.16	334
X6 - Insufficient Temporary Face Support	469	5.85	5,881
X7 - Improper Additional Roof Supports	797	9.95	9,033
X8 - Presence of Unsupported Areas	*	*	*
A2 - Management Error	**3,009**	**37.56**	**-**
B3 - Inadequate Training	**1,709**	**21.33**	**-**
C1 - Inadequate OSH Training	**917**	**11.45**	**-**
X9 - Inadequate Training of PPE Usage	175	2.18	1,732
X10 - Poor Safety Culture	742	9.26	8,617
C2 - Inadequate Job Training	**792**	**9.89**	**-**
X11 - Inadequate Training of Scaling	33	0.41	255
X12 - Inadequate Training of Support Installation	370	4.62	4,225
X13 - Inadequate Coal Excavation Training	199	2.48	2,579
X14 - Inadequate Training of Drilling and Blasting	46	0.57	518
X15 - Inadequate Training in Other Operations	144	1.80	1,472
B4 - Improper Equipment	**328**	**4.09**	**-**
X16 - Improper PPE	262	3.27	2,982
X17 - Improper Tools	66	0.82	872
B5 - Inadequate Planning	**972**	**12.13**	**-**
X18 - Insufficient Risk Assessment	879	10.97	10,299
X19 - Lack of Directives of Support	*	*	*
X20 - Giving Hazardous Tasks to Inexperienced	93	1.16	809
B6 - Insufficient Working Conditions	*****	*****	*****
X21 - Inefficient Salary	*	*	*
X22 - Long Working Hours	*	*	*
C3 - Unsafe Environmental Safety Conditions	*****	*****	*****

Table 4.1 All Failure Events and Frequencies in the FTA (Continued)

X23 - Poor Thermal Comfort	*	*	*
X24 - Poor Ventilation	*	*	*
A3 - Human Error	**2,272**	**28.36**	**-**
B7 - Unsafe Act	**1,240**	**15.48**	**-**
X25 - Failure to Take Control Measures	454	5.67	5,633
C4 - Equipment Related Failures	**256**	**3.20**	**-**
X26 - Disuse of PPE	162	2.02	1,528
X27 - Improper Use or Misuse of Equipment	94	1.17	1,238
C5 - Misapplication of Procedures	**530**	**6.62**	**-**
X28 - Support Installation and Removal Procedures	283	3.53	3,464
X29 - Drilling and Blasting Procedures	41	0.51	516
X30 - Coal Cleaning Procedures	24	0.30	155
X31 - Coal Excavation Procedures	112	1.40	1,963
X32 - Scaling Procedures	29	0.36	244
X33 - Maintenance and Repair Procedures	20	0.25	236
X34 - Transportation Procedures	21	0.26	336
B8 - Unsafe Condition	**1,032**	**12.88**	**-**
X35 - Accident Proneness	430	5.37	4,300
X36 - Inexperience	207	2.58	113
X37 - Physical Unsuitability	*	*	*
X38 - Poor Concentration	395	4.93	5,661
X39 - Lack of Motivation	*	*	*

* Undeveloped Event

Table 4.2 Severities of Basic Events

Basic Events	Severity (%) (Lost Days / Total Lost Day / # of Workers)
X18 - Insufficient Risk Assessment	11.16
X7 - Improper Additional Roof Supports	9.79
X10 - Poor Safety Culture	9.33
X3 - Failure to Control Preventive Safety Measures	7.98
X6 - Insufficient Temporary Face Support	6.37
X38 - Poor Concentration	6.13
X25 - Failure to Take Control Measures	6.10
X1 - Inefficient Scaling	4.97
X35 - Accident Proneness	4.66
X12 - Inadequate Training of Support Installation	4.58
X28 - Support Installation and Removal Procedures	3.75
X2 - Inefficient Support Inspections	3.36
X16 - Improper PPE	3.23
X13 - Inadequate Coal Excavation Training	2.79
X4 - Insufficient Roof Support	2.45
X31 - Coal Excavation Procedures	2.13
X9 - Inadequate Training of PPE Usage	1.88
X26 - Disuse of PPE	1.66
X15 - Inadequate Training in Other Operations	1.59
X27 - Improper Use or Misuse of Equipment	1.34
X17 - Improper Tools	0.94
X20 – Giving Hazardous Tasks to Inexperienced	0.88
X14 - Inadequate Training of Drilling and Blasting	0.56
X29 – Drilling and Blasting Procedures	0.56
X5 - Deterioration or Distortion of Support Elements	0.36
X34 - Transportation Procedures	0.36
X11 - Inadequate Training of Scaling	0.28
X32 - Scaling Procedures	0.26
X33 - Maintenance and Repair Procedures	0.26
X30 - Coal Cleaning Procedures	0.17
X36 - Inexperience	0.12

4.2.1 Engineering/Supervisor Error (A1)

Engineering and supervision error examined as the deficiencies in inspection and monitoring, inadequacies in taking proper prevention methods, and mistakes in the design phase and current design errors. Briefly, it can be defined as failures in control and design phases in the mine. In the fault tree (Figure 4.1), Inefficient Inspections and Controls (B1) and Support Design Error (B2) are combined with OR-Gate to A1. This means that if either of these events (B1 or B2) occurs, Engineering/Supervisor Error will occur.

There are two intermediate and eight basic events under Engineering/Supervisor Error. Frequencies, percentages, and lost days related to each event are given in Table 4.1. According to that table, Support Design Error (B2), has a higher frequency rate of accidents than Inefficient Inspections and Control (B1). Also, the most frequent basic event of Engineering/Supervisor Error is found as Improper Additional Roof Supports (X7). It is seen that, Deterioration or Distortion of support Elements (X5) has a minimum effect on both Engineering/Supervisor Error and the total system with 0.16%. Also, similar to frequency rates, the highest severe basic events among engineering supervisor are X7 (9.79%), X3 (7.98%), X6 (6.37%), and X1 (4.97%) as presented in Table 4.2.

4.2.1.1 Ineffective Inspections and Controls (B1)

One of the failures of engineering and supervisor error is found as 'Ineffective Inspections and Controls'. This event includes the accidents occurred due to lack of or inefficient inspections and poor monitoring of the mine environment. This includes both the inefficient scaling procedures, inefficient support inspections and insufficient preventive measures in the working area while or before tasks start as presented in Figure 4.2.

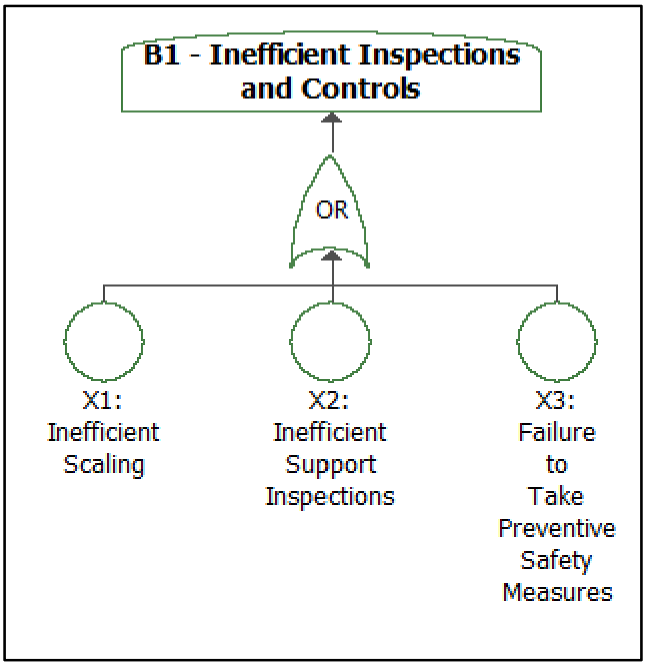


Figure 4.2 Fault Tree of Inefficient Inspections and Controls

<u>Inefficient Scaling (X1)</u>**:** The first basic event is named as Inefficient Scaling. Scaling can be described as removing the loose rocks from roof, face, and ribs. It is an important and one of the most dangerous tasks in underground mining and it could be severe or even fatal if it is not done properly. In the study area, manual scaling method is used. General procedure of manual scaling is conducted by visual inspection and by checking the sound of the rocks by experienced workers. While examining the working area, every side, roof, and corners need to be inspected. Escape ways, man ways, and main access ways should also be inspected as well as the working faces. Also, since coal excavation is a continuous procedure and it could affect the mine design in every operation, structures like loose materials, slabs, and loose rocks should constantly be watched as long as the excavation continues.

In the research area, most of the accidents occurred due to falls of small and medium loose rocks. Among these accidents, one of the main reasons is found as 'Inefficient Scaling', which corresponds to 355 (4.43%) accidents and 4,592 lost days (Table 4.1). While the data is examined, accidents from falls of rock and coal, and falls of loose rocks from the roof and ribs during or before coal excavation, support installation and removal, and other tasks like maintenance or drilling and blasting operations are considered.

Inefficient Support Inspections (X2)**:** Purpose of support systems in mines is to maintain the stability of the mine in the underground where the roof is not stable enough to carry itself. For an effective support system, all workers should eliminate or report the faults in the support system that they notice immediately in their working region, and supervisors are responsible for the safety of the working area, health and safety of the workers, and appropriateness of the support material. Also, in or near all of the working zones, there should be enough number of support materials with proper dimensions and qualification. In every part of the mine, supervisors and other engineers and foremen, who are responsible from the working zone, should ensure proper supports, and also they should ensure promptly made inspections and maintenance. Inspections should be made at least twice, at the beginning and at the end of the shifts (TTK, 2013).

In the study area support material in the faces are timber supports and cribs, and in the main access ways, steel supports with timber supports are used. Inspection of these supports should be made to determine which of them need maintenance, or which of them need to be replaced in order to prevent accidents due to support collapses or deteriorations. In Figure 4.3, an example of an inadequate support from the research area is presented. This photograph was taken during one of the site visits with n ex-proof camera, and there were also other similar examples detected during these visits. This also shows that there is inadequate support inspection in the study area. Besides, when the data were examined, it was seen that there were 271 occupational accidents occurred related to ‘Inefficient Support Inspections’ which resulted in 3,103 lost days of work (Table 4.1), with 3.36% severity (Table 4.2). This data only includes the suitability of the present supports and control, and monitoring the efficiency of the current system in the mine. Accidents due to lack of efficient support and their inspections are also considered.

Figure 4.3 An Example of an Inadequate Support in the Study Area

<u>Failure to Take Preventive Environmental Safety Measures (X3):</u> Besides of scaling and support inspections, before the task starts, environmental safety should be maintained in the working area. Any hazard that could result in accidents should be eliminated. According to 18001–Occupational Health and Safety Management Systems (OHSAS-18001), occupational health and safety performances should be monitored and inspected regularly. Monitoring should include the efficiency of the prevention methods as well as the performance of qualitative and quantitative proactive and reactive measures. This includes both monitoring of the ground support systems and mining area before the employees start working. Also, monitoring and inspection data should be recorded for improvement of the mine safety. Besides, another reason for monitoring and inspections are to explain the employee which hazards and risks exist in the working area, and which actions should be taken (Oraee *et al.*, 2011).

Accidents related to 'Failure to Take Preventive Environmental Safety Measurements' are caused by rock and coal falls from the roof and ribs, subsidence, slabs, sloughing, and fall of loose rocks. Reasons for these incidents are ineffectiveness in ensuring environmental safety and inefficiency in taking necessary measurements. During scaling and support controls, these hazardous conditions should also be inspected. Supervisor's duty is to ensure that there is not any loose rock or hazards of rock fall in the study area and also to ensure the used equipment are safe and will not cause any additional damage to the worker while they are performing their tasks. It is found that there were 620 accidents related to this basic event, which corresponds to 7.74% of all system, and results in totally 7,365 lost days (Table 4.1). The accident rate of this failure event is quite high when compared to other events, which means that this failure is one of the most important events that should be prevented as soon as possible in the evaluation of FTA phase.

4.2.1.2 Support Design Error (B2)

In order to prevent the accidents, it is important to understand the hazards and conditions of the mine and then install the support elements. While installing ground and rock supports, both surrounding of the rock mass, infrastructure of the mine, and the condition of the excavated vicinities and faces should be considered. Stability of the mine is dependent on many elements such as, the structure and nature of the ore body, geological disturbances, groundwater conditions, in situ stresses, geometry of the openings, and excavation method in the mine. Ground support includes the terms of both rock reinforcement and surface rock support. Rock reinforcement are supports directly installed to rock mass like rock bolts, and surface rock support are supports applied to the surface of the rock mass like mesh and strapping. Support means all types of timber and steel supports, bolts, dowels, friction rock stabilizers, mesh, straps, shotcrete, hydraulic props used to ensure the stability of the mine openings (The Government of Western Australia-Mines Occupational Safety and Health Advisory Board, 2000).

It was found that the majority of the accidents were from skin failures. This generally occurred in the unsupported parts of the mine or from between the voids of the timber supports. Support design error indicates inadequacies and deficiencies in the ground support. In the study area there is not any additional support or reinforcements like bolts, shotcrete or hydraulic support used in the support system. In the faces and drifts, timber supports and timber cribs are used. Type of the trees that are used in timber supports are oak, hornbeam, beech, and pine trees. In the main access ways, steel and timber sets are used. Since 2010, T-H sets have been started to be used in the mine as an alternative to timber and steel sets in the main access ways. The use of T-H supports makes the control of alignment and direction of headings easier and it is practical in high vertical and lateral pressured formations since it can resist long term pressure, and also its installation requires less labor and its long-term maintenance and repair costs are relatively low (Turkish Count of Accounts, 2013).

When the incidents were examined, it was seen that some accidents could be prevented if there were proper additional support or reinforcements to prevent the falls of small coal and rocks or loose rock. In this manner, the unsupported areas could be supported by reinforcement methods and also voids between the permanent supports could also be supported by additional supports.

Fault tree of support design error is presented in Figure 4.4. Main failures related to support design error are found as; ‘Insufficient Roof Support (X4)’, Deterioration or Distortion of Support Elements (X5)’, ‘Insufficient Temporary Face Support (X6)’, ‘Improper Additional Roof Supports (X7)’, and ‘Presence of Unsupported Areas (X8)’.These events are connected with an OR-Gate as presented in Figure 4.4. This means that failure of either of these events will result in a support design error.

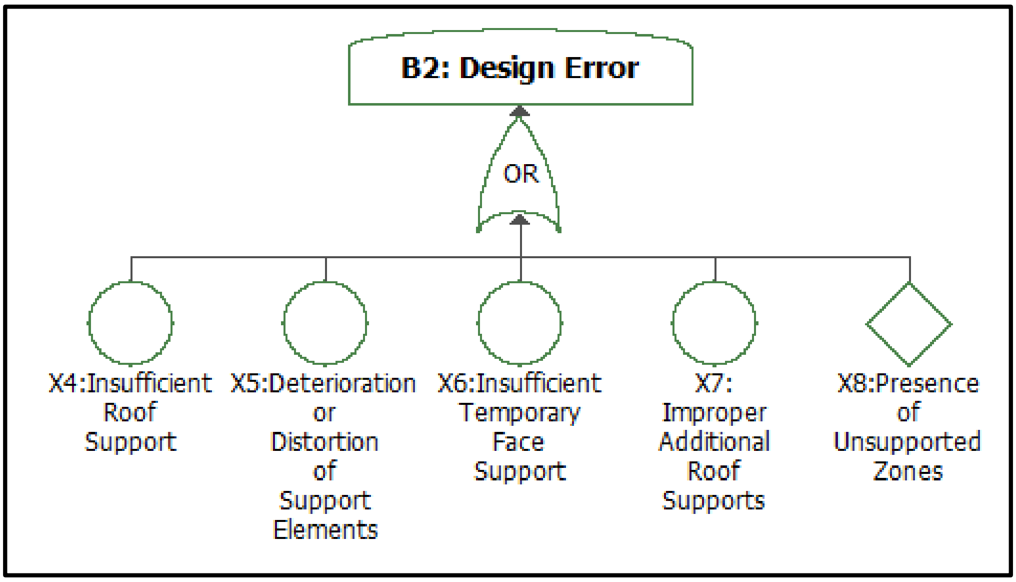


Figure 4.4 Fault Tree of Support Design Error

Insufficient Roof Support (X4)**:** Accidents caused by rock falls from the roof are particularly examined for this failure event. Poor roof support in underground mines leads small rock and coal falls from the roof and ribs. Roof support should be capable of stable in order to avoid small, medium, and large rock falls. When the data is examined, some causality's reason is found as insufficient support system of roof. In the faces and drifts supports used in the roofs are timber supports and also timber cribs are used to carry the load of the roof instead of props. However, there are still some deficiencies in the roof support since there were 206 accidents occurred due to roof support failure within eleven year period (Table 4.1) with 2.45% severity (Table 4.2).

Deterioration or Distortion of Support Elements (X5): Support materials can deteriorate or distorted in time and if they are not inspected periodically in drifts, occupational accidents may occur. Because of this deterioration, support materials can collapse or break and jeopardize workers' life. In order to prevent these accidents, firstly strong support should be chosen in compliance with technological improvements. Also, long-lasting support material should be preferred in the main roadways. Maintenance of the support material should be made periodically. Furthermore, support should be monitored and inspected regularly and repair or alteration with new support materials should be provided if required. In the study area, some distorted or broken support was examined. However, it was found that only 0.16% of the total accidents are related to this failure. This means that, whether the accidents were not caused due to that failure or it was not mentioned in the accident data.

Insufficient Temporary Face Support (X6): Since June 2009, pneumatic inflatable pillows have been used between crib materials in order to improve the safety and recovery of the timber material, and also to ensure faster and safer dissembling and installation (Turkish Count of Accounts, 2013). Besides of this important improvement, there are still some deficiencies in the support system. Especially in the faces, 469 occupational accidents occurred between 2003 and 2013 due to this inadequacy (Table 4.1). The causes of these accidents are analyzed in the fault tree and reasons of these accidents occurred generally due to insufficiency in preventing face sloughing and loose rocks. One of the most significant problems in the study area is accidents occurred because of coal and rock falls. This is also valid for face and drifts and these accidents generally occur from fall of smaller rocks. Besides of efficient scaling, in order to avoid the accidents due to loose rock, efficient temporary support systems should also be installed within the working faces. Supports in the faces should be stable and should not be affected by any geologic disturbances or other operations like drilling or blasting. There should be a proper face support in order to avoid crumbling and sloughing from the drifts and faces.

Improper Additional Roof Supports (X7)**:** Additional roof supports means cribs, roof bolts, mesh, shotcrete, and other similar support systems that are used to aid the primary support system. As it has mentioned before timber cribs are used in the faces as additional roof supports. However, during the site visits it has seen that there are some improperness in the crib support systems. For example, some of these supports are not well constructed to carry the roof and some of them tend to be dispersed due to the wrong installation.

Also, for the main access ways, there isn't any bolts used. Rock bolts are used to transfer the load from the unstable exterior rock mass to the interior rock mass. Roof bolts are used as a primary support. Peng (2008) stated that, the use of roof bolts reduced the number of fatal and nonfatal accidents in the U.S. coal mines. Also, Brandt and Cassie (2002) stated that roof bolts reduces the maintenance, increases the production, and decreases the cost (Peng, 2008).

Besides, there wasn't any meshes used to prevent skin falls in the mine. Meshes are used to prevent falls of smaller rocks from the roof and ribs. The best way of preventing accidents due to small rock falls is using wire mesh or roof screening because they can cover all the gaps between the permanent supports (Compton *et al.*, 2005). However, roof screen installations are generally done with bolt installations and since there are not any rock bolts used in the mine, there is not any roof screen or mesh either. Also, other additional roof supports and reinforcements such as, shotcrete, cable bolts, dowels *etc.* are not used in the study area. When the accident data is examined, it is seen that a great majority of the accidents occurred due to the improper additional support with related 797 accidents (Table 4.1). Also these accidents resulted with 9,033 lost days and 9.79% severity (Table 4.2). It can be said that, since the most of the accidents occurred as relatively smaller rock falls, if additional supports are used in the research area, a considerable amount of accidents could be prevented.

***Presence of Unsupported Areas (X8)*:** In most underground mines, there are unsupported areas which do not need any permanent support thus rock could carry its own mass. However, even if permanent support is not necessary, there should be support systems in order to prevent skin falls. This situation is also valid for the research area. There are some unsupported areas, and generally rib falls occurred in these regions. However, in the accident data, there is not a reliable information about such cases. Because of that, it was decided to evaluate this event as the undeveloped event in the fault tree analysis.

4.2.2 Management Error (A2)

Management responsibilities of sustaining occupational health and safety are one of the most important factors among all causes of occupational accidents. According to the regulations throughout the world, obligations to sustain occupational health and safety are always on behalf of the employees. According to Occupational Health and Safety Law No: 6331 of Turkey, obligations of employers are also one of the main, perhaps the most important factor. According to this law, employers are obligated to provide health and safety of the employees. Within this scope, employers need to do necessary work to prevent occupational risks, to take all necessary measures, including providing training and information, fulfillment of the organizations, providing the necessary tools and equipment, to be adapted to the changing conditions of health and safety measures and improvement of the current situation. Employers should monitor and inspect whether the rules of occupational health and safety is applied or not and eliminate the unfavorable conditions about occupational health and safety. They are also responsible for risk assessments to be done in workplaces. Employees' convenience in terms of safety and health need to be considered about the tasks they will perform. Necessary precautions need to be taken for workers not to enter hazardous and vital areas. Also obligations of the employee in the occupational safety and health area does not affect the responsibilities of the employer (MoLSS, 2012a).

According to Occupational Health and Safety in Mining Workplaces Regulation, mining sites should be designed, built, equipped, operated, and maintained in order not to jeopardize employees' health and safety. Every operation must be conducted and completed under the supervision of an authorized person. Works with the specific risks could only be made on the inspection of a competent person who is specifically trained about those specific jobs and they should be made according to the instructions. All of the safety instructions must be prepared clearly in order for employees to understand easily (MoLSS, 2013a). In general, management should provide safe working conditions in accordance with efficient measures to promote occupational health and safety. All of the issues related to training, planning, equipment provision, and working conditions are related to decisions of the management.

According to this information, in the study area, the management failures were categorized into four sub-failure events as; 'Inadequate Training (B3)', 'Improper Equipment (B4)', 'Inadequate Planning (B5)', and 'Insufficient Working Conditions (B6)' as presented in Figure 4.1. All events are connected with Voting-Gate to A2. The reason for this is that, none of B3, B4, B5, and B6 is enough to generate an accident. Similarly to the fault tree of the entire system as mentioned at the beginning of this chapter, in order to management error to be occur, at least two of these failure events need to arise together for a roof and rib fall accident. Each of these events are explained in detail in the following sections. The frequency distribution of each failure events of Management Error is also given in Table 4.1. It is seen that, Hard Working Conditions (B6) cannot be analyzed due to lack of sufficient accident data and events under which stay as undeveloped events. The most significant secondary event here is found as Inadequate Training (B3) with 21.33%. Also, insufficient risk assessment (X18), and Poor Safety Culture (X10) play significant role among management error failures with their high frequency rates. Besides of that, similarly to most frequent basic events, most severe events among management error are found as X18 (11.16%), X10 (9.33%), and X12 (4.58%).

4.2.2.1 Inadequacy in Training (B3)

Safety subjects relevant to ground conditions and control must be included in training programs and all of the required training must be provided to miners before they begin work in a mine or before they receive new work tasks or assignments. Each worker should understand how to identify hazardous ground conditions and safe mining practices to keep them safe (Oraee *et al.*, 2011).

As it has mentioned in Chapter 3, before workers start the job, they take an adaptation training program. Also, renewal training is given periodically. Besides of this, individuals who change their professions or remain separate from work or at least six months are given the refresher training, and individuals who remain separate from their job for two years are taking the adaptation training from the beginning. However, when the accidents were analyzed, it was seen that there was an inadequacy in workers' training. Some accidents could have been prevented if proper occupational health and safety trainings or proper job trainings were given. This means that there still is some inefficiency in the training program of the company. These inadequacies are evaluated under 'Inadequate Occupational Health and Safety Training' (C1) and 'Inadequate Job Training' (C2) as can be seen from Figure 4.5. C1 and C2 are connected to B3 with an OR-Gate. Also, events under C1 and C2 are connected with OR-Gates. This means that, any of these basic event occurrence leads to an inadequate training in the fault tree.

Inadequate Occupational Safety and Health Training (C1)

There are unsafe acts and unsafe conditions in safety literature. Unsafe act is a human error in which the worker knows how to perform the task, what should or should not be done, however, do not perform the task properly or do not do the right thing. In other words unsafe act takes place when the worker has behavioral problems. On the other hand, if the workers did not take the proper training on the tasks or safe behavior, then the situation should be evaluated under management error for not giving the proper training to workers. In the fault tree analysis, occupational safety and health training composed of inefficiency in sustaining safety culture and inadequacy in giving proper training for Personal Protective Equipment (PPE) usage. The main purpose of occupational health and safety training should be ensuring the change in workers' behaviors and also to improve safety culture and ensuring a raise of awareness of the dangerous, hazardous, and risky situations.

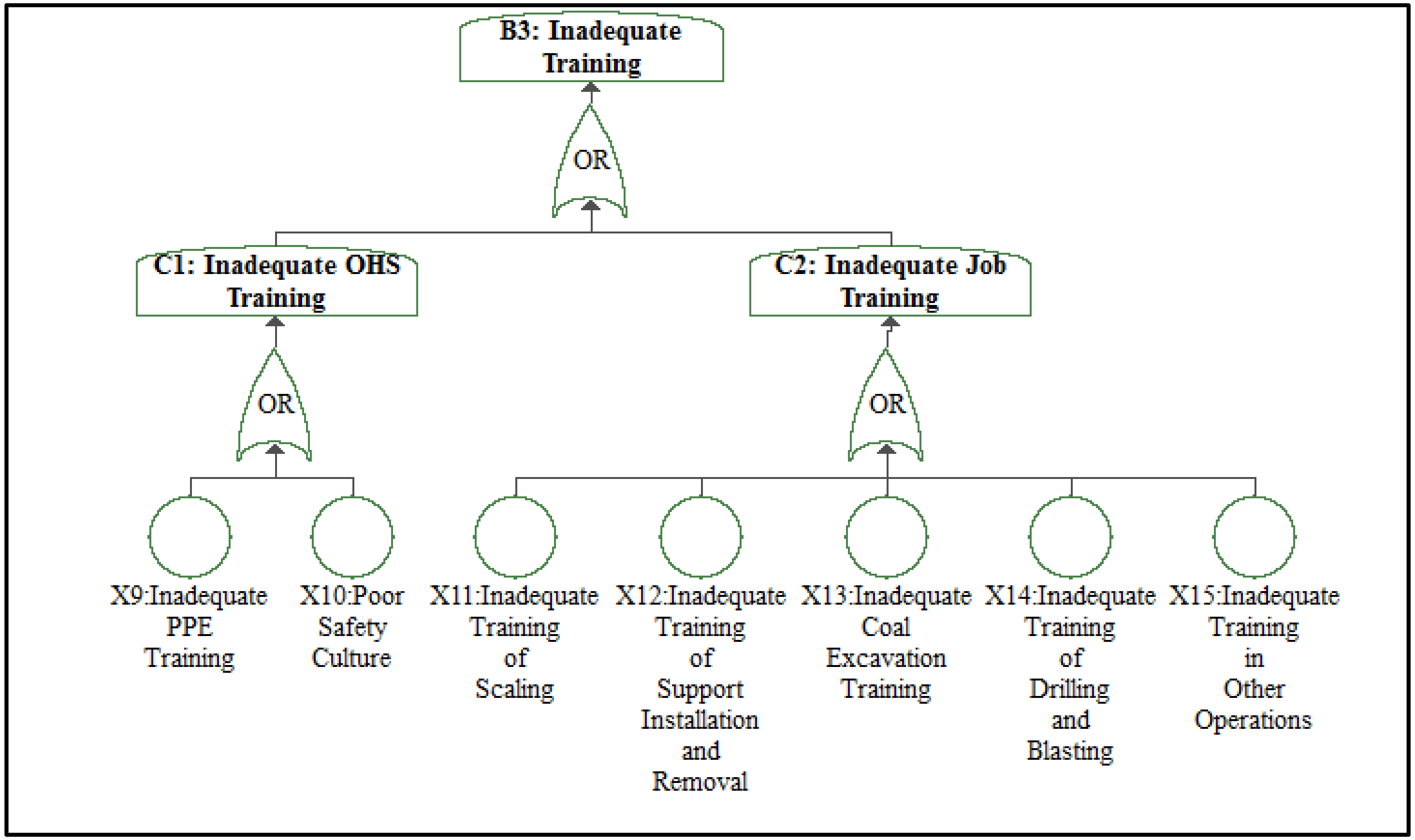


Figure 4.5 Fault Tree of Inadequate Training

Inadequate Training of Importance of Personal Protective Equipment (PPE) Usage (X9): The basic reason for not using PPE can be defined as insufficient training of the importance of PPE usage. Also, lack of some enforcements to workers in order to make them use the given PPE for their safety and health can be given as another reason. If a qualified training and education about PPE usage is given and workers still do not want to use them, it becomes a behavioral issue and should be dealt as human error, as unsafe act. Also, if there is a poor thermal comfort or if the PPE are uncomfortable, this situation should be considered as inadequate equipment or poor environmental conditions. In the accident data, it is seen that there were accidents due to not wearing hard hats or protective glasses and other similar personal protective equipment even if the management provided and they are competent technologically. These accidents are evaluated under this basic event as inadequate training.

Poor Safety Culture (X10): Zohar (1980) defined safety culture as a common set of safety related attitudes, perceptions, and behaviors between people. Assessment of safety culture in an organization helps supervisors to monitor and understand the current behavioral safety process. Management has a leading part in sustaining safety environment and conducting a safety culture. In order to ensure safety in workplaces, management's contribution to safety procedures like giving recommendations and opinions in risk assessment processes or giving feedbacks to workers plays a key role (Wirth and Sigurdsson, 2008).

According to a study of Parker *et al*. (2006), there are five types of safety approaches; pathological, reactive, calculative, proactive, and generative. This approaches begins from the least safe to safer attitudes. For example, in pathological approach, the understanding is not giving enough attention on safety and safety precautions. Reactive attitude approaches safety as necessary precautions should be taken if any accident occurs in the workplace. The calculative approach has systems to manage the hazards in the workplace. Proactive behavior is based on taking precautions before any accident occurs. Lastly, generative approach is the safest and the most proactive such that, occupational safety and health is the primary concern for these workplaces (Hecker and Goldenhar, 2014).

Turkish regulations adopted proactive approach with the Law No.6331 in 2012 and since then, inspections and legislations have been based on to this approach. However, the study area more likely has the reactive approach. Safety is important for the company for sure, but also necessary precautions are taken if any accident occurs. This attitude and behavior could only be changed with qualified training and education of management, engineers, supervisors, and front line workers. Also lack of safety culture is not only constituted by training, it can also sustain by proper education and by safe behaviors of management and supervisors. It could be said that approximately in all accidents in the research area, poor safety culture plays a key role. There were 742 accidents related to poor safety culture in the FTA (Table 4.1).

Inadequate Job Training (C2)

After theoretical training given at the beginning of the job, inexperienced workers start working near experienced chief operators. During this period they learn the procedures of the tasks that they will perform and they do not start main tasks alone until they learn the procedures efficiently. However, when the data is examined, it is found that there were still some inadequacies while implementing the procedures, especially during support installation and removal, drilling and blasting, scaling, coal excavation, maintenance, and material transportation.

Inadequate Training of Scaling (X11): The safest way to scale the area is to firstly scaling the roofs, then the ribs and then the face. It should also always be scaled from good to bad ground. It is also important to ventilate the operating area to clean the dust and also after blasting, the area should be watered down in order to visually inspect loose rocks. If any loose rock is detected, but could not be barred down manually, then it should immediately be reported to a supervisor (MSHA, 2008). In the working area, there were accidents occurred while scaling roof and ribs due to fall of loose rocks.

Workers should learn to protect themselves from falling loose rocks and this could be done by qualified scaling training and proper PPE usage with proper scaling equipment. There were 33 accidents occurred while scaling in the research area during the evaluated time period (Table 4.1).

Inadequate Training of Support Installation and Removal (X12): Most of the accidents about deficiencies in training occurred while installing or removal of support materials (Table 4.1). Besides of taking proper preventive measures in the working area, it is also very important for workers to be sufficiently trained about their tasks. Sufficient training in support installation and removal tasks should include both the practical training and also taking preventive measures both for themselves and for coworkers. Also, the importance of using equipment safely and accordingly only for its purpose is another concern that needs to be added in training programs.

Inadequate Coal Excavation Training (X13): There are 199 accidents occurred while coal excavation (Table 4.1) because of insufficient trainings of the workers. These accidents are generally due to wrong practices, working without taking proper preventive measures, and improper use of equipment.

Inadequate Training of Drilling and Blasting (X14): There were 46 occurred during drilling and blasting operations (Table 4.1). Drilling and blasting operations in the study area are made by an experienced operator and there is another worker who works as an apprentice and an observer. During the site visits it was recognized that drilling operators work without taking proper safety precautions. During drilling and blasting operations rock falls from the drilled area is an expected situation since the strata of the mine is being changed by exterior forces. From the accident records it is seen that most of the accidents occurred during drilling are due to small and medium rock falls from the drilled area. With a proper training to drilling operators such accidents could be prevented.

<u>Inadequate Training of Other Operations (X15):</u> There are 144 accidents occurred in other tasks due to inadequate training (Table 4.1). These operations are cleaning of coal and/or environment, repair and maintenance, and material transportation. Most of these accidents occurred because of improper practices due to insufficient training.

4.2.2.2 Improper Equipment (B4)

One of the management's duties is to ensure proper equipment for workers' health and safety. These equipment should be safe for tasks and should not constitute any additional hazards. For example, during manual scaling, workers must wear PPE, especially hard hats, safety glasses, and proper foot protectors. Scaling bar and its appropriate utilization is also important in the scaling procedure and in preventing any additional accidents from occurring. Providing suitable PPE and proper tools are one of the most important duties of the management.

In the study area, improper equipment related failures are found as 'Improper PPE (X16)' and 'Improper Tools (X17)'. These events are connected with an OR-Gate as shown in Figure 4.6. Occurrence of either of X16 or X17 means at least one accident occurred due to an effect of improper equipment.

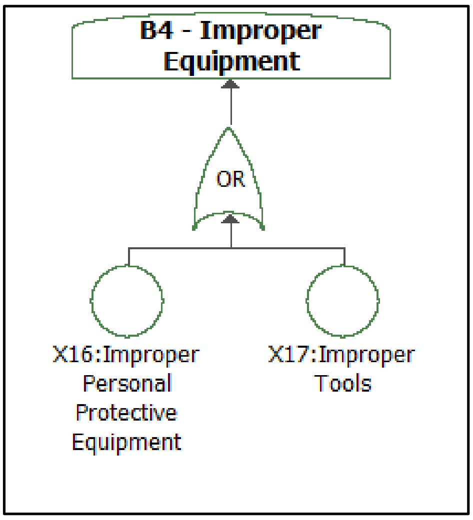


Figure 4.6 Fault Tree of Improper Equipment

Improper Personal Protective Equipment (PPE) (X16): Another important factor that leads to occupational accidents is inefficient or lack of personal protective equipment (PPE). It was mentioned in X9 that, some accidents occurred due to inadequate training of importance of PPE. In this basic event this time, appropriateness of the PPE is examined. It should be mentioned that general preventive measures are prioritized than personal protection. However, in industries like mining and especially in underground mining, PPE are highly critical. If the general preventive measures are insufficient, PPE need to protect the workers. In such circumstances, if the available PPE are not proper enough for the task or if workers do not have the essential PPE, then accidents become inevitable.

According to Personal Protective Equipment Regulation of Turkey, PPE are used if the risks cannot be prevented with technical precaution measures or work organization or procedures. All PPE should be proper for avoiding risks and should not create any additional risks. They should all be suitable for working conditions and ergonomic. Also, they must have a CE sign on them. If more than one PPE should be used according to the task, then all PPE must be available at the same time without generating any additional risks. Management should inform workers about which PPE should be used for which risks (MoLSS, 2013b).

In underground mining, main PPE are head protectors, eye protectors, face protectors, hand and arm protectors, foot protectors, hearing protectors, and respiratory protectors (OSHA, 2003). Roof and rib fall accidents in the study area are especially from strikes, cuts, crashes, and smashing of rocks. According to the data, in Figure 4.7, the number of injured body parts during 2003-2013 according to the data gathered from TTK is given. It can be seen from the figure that most injured body parts are hands and wrists following by feet and ankles. However, main necessary PPE to avoid injuries due to roof and rib falls are head protectors, eye protectors, and foot protectors since the injuries are due to strikes, cuts, crashes, and smashing of rocks. Other PPE like protective gloves and protective clothing are not able to avoid such injuries.

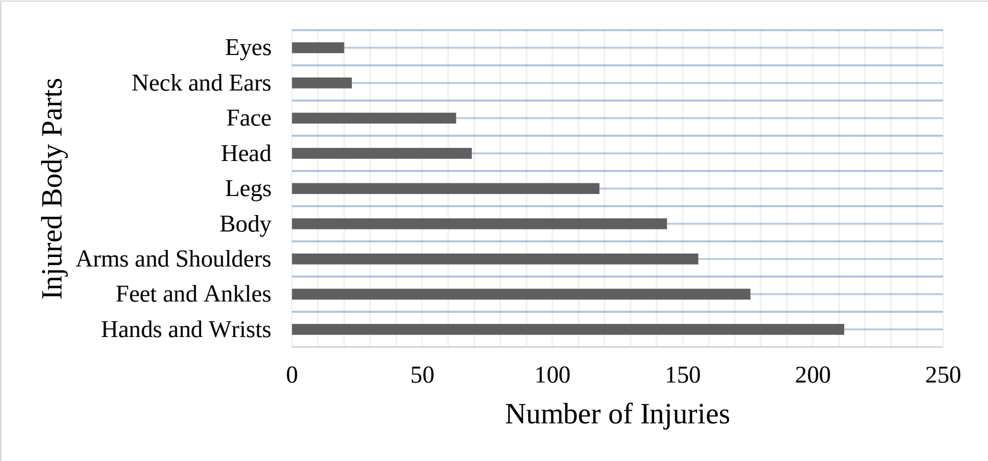


Figure 4.7 Injured Body Parts between 2003 and 2013

It is important to know here that in an accident, workers can be injured by several organs at the same time such that there are more than one injured body parts for some of the accidents. In the study, only foot, head, and eye injuries are included in the FTA for the improper PPE basic event. Basic events that trigger the accidents due to roof and rib falls were failure to provide appropriate protective equipment or PPE were not suitable enough in terms of technical and technological aspects for the tasks. Also, another concept is despite the fact that management provides suitable PPE with proper training and workers will not use the PPE, then this is considered as a basic event under ‘Human Error’. According to these information, there were 262 accidents occurred related to this basic event in the study area (Table 4.1).

***Improper Tools (X17)*:** In this failure event, equipment related accidents were examined. There are totally 66 accidents related to improper tools and these accidents occurred mainly during scaling and drilling and blasting operations (Table 4.1). As it was mentioned in the ‘Ineffective Scaling’ part, during the scaling procedure the equipment used is called a scaling bar. There are several kinds of scaling bars with various lengths and specifications. Structure of scaling bar is composed of a straight chisel point on one end and a heel and chisel point toe at the other hand for a better control. In general, aluminum bars are longer than solid steel bars because they are lighter. In areas with high backs usually aluminum bars are preferred because of their long lengths since operators can keep away from falling rocks. Disadvantage of the hollow ones is that they are not as useful as steel bars in sound checking. This situation makes the use of hollow bars in confined spaces and in high headings impractical (Government of Western Australia, 1997). During site visits, it was seen that for scaling, workers sometimes use vacant timber support parts as scaling bars. The length and required specifications of scaling bars are ignored. The only purpose of using such equipment is to drop the loose rock whether or not it has additional risks. In these circumstances, accidents during scaling become inevitable.

4.2.2.3 Inadequate Planning (B5)

Effective planning from the design phase till the current excavations and support systems plays a key role in occupational safety and health. There is a General Preventive Measurements Circular of the company and preventive measures about subsidence, accumulation of gas and ventilation, fire and explosion, use of drilling and blasting equipment, electrical hazards, transportation, mechanical hazards, and inspections take place in this circular (TTK, 2013).

However, there is still some inefficiencies about risk assessment and support planning in the company. These are examined as; ‘Insufficient Risk Assessment (X18)’, ‘Lack of Directives of Support (X19)’, and ‘Giving Hazardous Tasks to Less Experienced Workers (X20)’. These failure events are connected with an OR-Gate as shown in Figure 4.8. X19 is evaluated as an undeveloped event in the fault tree, due to lack of efficient data about accidents because of lack of directives of support.

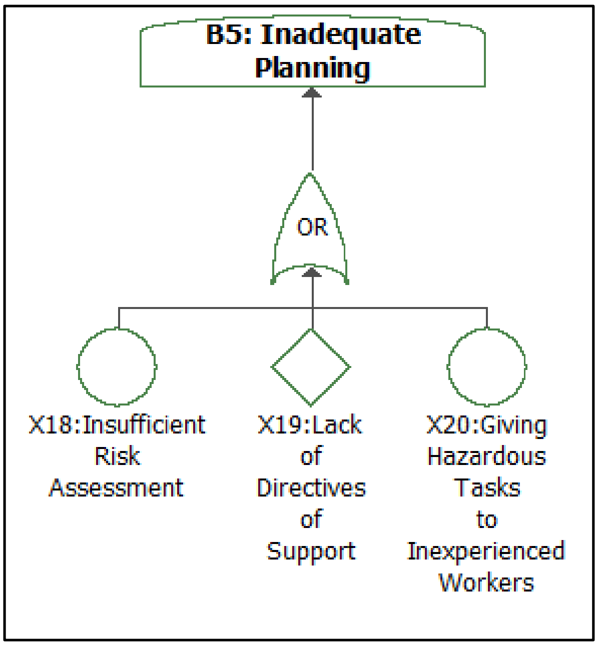


Figure 4.8 Fault Tree of Inadequate Planning

<u>Insufficient Risk Assessment (X18):</u> According to Occupational Health and Safety Risk Assessment Regulation, employers should conduct risk assessments in every workplace in order to provide, maintain, and develop occupational safety and health of employees and safety of the working environment. Risk assessment is conducted in all parts of workplaces which begins with the design phase and carrying out by describing the hazards, defining and analyzing risks, determining preventive measures, documentation, updating the works and revising when necessary. It is important to engage workers in every phase of risk assessment (MoLSS, 2012b).

Risk assessment of the company was examined and it was seen that the assessment was not sufficient enough for the needs of the workplace. The risk analysis was made in the form of 5x5 matrix. There are several risk assessment methodologies are present for risk assessment. The main purpose of the risk analysis should be defining the present hazards in workplaces and take preventive measures accordingly and it could be done using any methodology. The 5*5 matrix method can be a sufficient method for the research area, however, there are various deficiencies in this analysis. An example of a part of this risk assessment was given in Chapter 3. Firstly, there was a lack of hazard classification and hazards written in the analysis was not enough and was not reflected all the dangers and hazards present in the workplace. Also, hazard and risk concepts were confused with each other. Nearly all of the hazards were found in low risk level. Risks were evaluated superficial and the results of the risks were incomprehensible. Also present preventive measures were inadequate and preventive measures to be taken were not present in the analysis. In line for this situation, risk assessment should be revised and all existing hazards and risks should be added and preventive measures to be taken should be written in detail according to company's needs in the analysis.

An effective risk analysis is a very important step in determining the existing hazards in the workplace and the decision of the preventive measures. An insufficient risk analysis is the reason for insufficiency in defining hazards and insufficiency in preventing accidents. Risk analysis should be applied to every task in underground as well as every hazardous zone. While evaluating the FTA, insufficient risk analysis is assumed to be one of the reasons of all accidents and due to that reason, this basic event is examined as one of the reason of all 879 accidents as can be seen from Table 4.1.

Lack of Directives of Support (X19): In the Regulation of Occupational Health and Safety in Mining Workplaces, there are some mandatory directives that need to be present in every mining workplace. One of these directives is 'Directive of Supports'. This directive should include staff who is responsible for supports for every supported area, safety precautions during the construction and installation of supports, quality, amount and size of support equipment which should be present in every working face, precautions for the proper support construction according to the specialty, geological and tectonic structure, physical and chemical properties of the working faces, precautions of support construction for the mines which are gassy or prone to spontaneous combustion and recovery of the roof support (MoLSS, 2013a).

In the study area, there is a lack of directive of supports. The reason of this was explained by the company as an ongoing revision of the previous directive by means of compliance with the current regulations. Although, between the years 2013 and 2015 while this study was conducted, directive of the supports was missing and it takes place in the FTA as 'Lack of Directives of Support'. Though, since the probability of this event could not be related to the accidents due to lack of additional information and data, this failure event takes place as an undeveloped event in the FTA.

<u>Giving Hazardous Tasks to Less Experienced Workers (X20)</u>**:** Mining is one of the most hazardous jobs and it needs experience to get used to its challenging conditions and behave safely. Thus, workers who are less experienced tend to be more prone to accidents than experienced ones especially in mining. Leflamme and Menckel (1995) stated that, as the experience increases, familiarity with the tasks and work environment also increases. Some studies found that, more experienced workers are able to use resources more competently in order to avoid accidents and therefore they are less prone to accidents rather than inexperienced workers (Margolis, 2010). In this circumstance, planning of the inexperienced workers' tasks requires more attention.

In the study, while this failure event was examining, especially injuries of three years or less experienced workers' relatively hazardous tasks were considered. There were 207 roof/rib fall accidents occurred to three years or less experienced workers and among these accidents 93 of them (Table 4.1) are found to occurr while doing hazardous tasks. That requires reassignments accordingly to give these tasks to more experienced workers. These accidents occurred mainly during drilling and blasting, support installation and removal, repair, and scaling operations. Tasks like assist to experienced operators during drilling and blasting or support installation and removal did not include in this failure event, in fact, these assisting tasks are the actual tasks that less experienced workers need to be assigned to.

4.2.2.4 Insufficient Working Conditions (B6)

Management's another duty is to ensure better working conditions for employees. These conditions to be sustained are all present in legislations and regulations. These conditions take part in the study as 'Insufficient Salary (X21)', 'Long Working Hours (X22)', and 'Unsafe Environmental Conditions (C3)' as shown in Figure 4.9. These two basic events and one intermediate event are connected with an OR-Gate to B6. These failure events do not depend on accident data that were gathered from the company but, they are more likely to depend on conditions that experienced during site visits and research. Because of that, these events only could be evaluated qualitatively and take part as undeveloped events, and did not include in the quantitative fault tree.

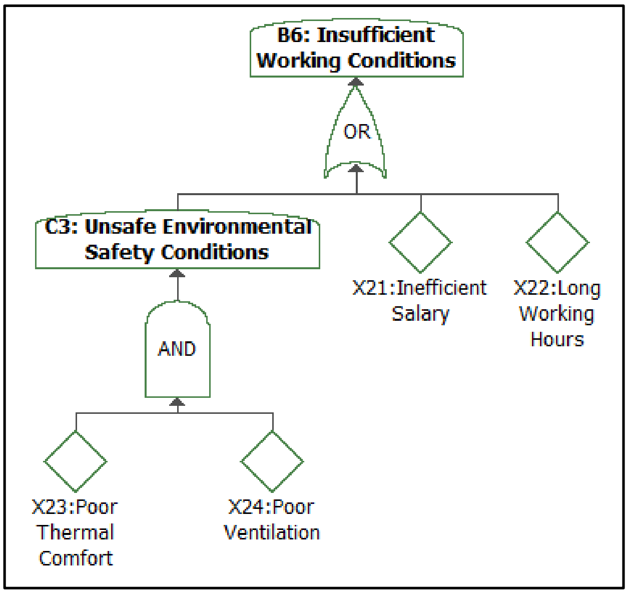


Figure 4.9 Fault Tree of Hard Working Conditions

<u>Insufficient Salary (X21):</u> Low income is one of the factors of psychological risks at work that generates work stress. Work stress is due to several factors like, poor payment, the nature of the job, working conditions, and co-workers. Also age, gender, marital status, and educational level have effects on work stress. In this study, low salary takes place as one of the causes of accidents due to the fact that it affects workers psychological phases.

It is a known fact that, miners in Turkey have lower salaries relative to miners in developed countries. A survey conducted by global recruitment firm HAYS (2013) showed annual base salaries of miners worldwide in US dollars (Table 4.3). According to that survey, among countries that take place in the study, the lowest salary is in Kazakhstan with 22,500 $, and the highest salary is in Norway with 158,700 $, an average of salaries of countries included in the survey is 63,178 $.

Table 4.3 Annual Salaries of Miners around the World (HAYS, 2013)

Country	**Local Average Annual Salary ($)**	**Country**	**Local Average Annual Salary ($)**
Norway	158,700	Poland	51,800
Australia	137,100	China	51,400
Canada	101,800	Botswana	49,500
Germany	99,100	Zambia	48,600
USA	96,900	Spain	48,500
Chile	92,200	Namibia	47,700
Ireland	90,900	India	46,000
UK	89,100	Mozambique	45,100
New Zealand	85,300	Malaysia	43,400
Brazil	76,800	Russia	42,700
Peru	73,100	Argentina	41,600
South Africa	68,400	Zimbabwe	41,200
Colombia	61,100	Angola	40,800
Italy	57,400	Indonesia	40,300
Mexico	56,100	Ghana	39,200
Ukraine	54,200	Mongolia	35,400
Congo (DRC)	53,000	PNG	35,200
Bolivia	52,300	Kazakhstan	22,500

Underground workers' salary in the study area is approximately 3,300 TL but with the insurance premiums, taxes, and other social rights, workers have approximately 1,300 TL monthly. Annually the amount of salary and discounted salary of the underground workers in the study area is approximately 15,840 $ and 6,240 $ respectively, which is way too less than the worldwide average and also lower than the lowest salaried country in the survey of HAYS. Also, according to a survey conducted by Durşen (2014), the majority of participants that work in the study area stated that they have between 1,500 – 2,500 TL per month (Durşen, 2015). In the study, this failure event takes place as an undeveloped event, since there is not any information about the relationship between the accident occurrence and salary in the data. Instead, it is decided to be evaluated only in the qualitative part of the study.

***Long Working Hours (X22)*:** In a study that Greenwood conducted among munition workers during the First World War, it was seen that when the working hours were decreased, there was a reduction in the number of accidents that, there was a linear relation between working hours and accident number (Froggatt and Smiley, 1964). In the study area, degree of difficulty of underground mining should be considered and working hours should be limited accordingly. There are 3 shifts per day and every shift is 6.5 hours long. According to data gathered in April 2015, in the first shift (08:00-14:30) there are 254 employee work in underground, in the second shift (16:00-22:30) there are 144, and in the third shift (00:00-06:30) there are 120 employee work in underground. In the same survey, 95% of the participants' state to work six days in a week and 40% works two or three shifts. Similarly to insufficient salary, this failure event also takes place as an undeveloped event in the fault tree. The information is insufficient to correlate insufficient salary and work accidents in the research are.

Unsafe Environmental Safety Conditions (C3)

Management's another duty is to provide sufficient environmental conditions such as, sufficient thermal comfort and sufficient ventilation in the mining workplaces. During site visits, it was observed that in some areas in underground, temperature is higher than it is meant to be and air amount and velocity varied from place to place that somewhere it was high and somewhere air quality was felt to be poor.

Unsafe environmental safety conditions are considered under two basic events, 'Poor Thermal Comfort (X23)' and 'Poor Ventilation (X24)'. These are connected with an AND-Gate to C3 (Figure 4.9). This means that, for an unsafe environmental safety condition both X23 and X24, should be failed together.

Poor Thermal Comfort (X23): Poor thermal comfort means high or low temperature in workplaces or if the workers exposed to radiant heat, warming up because of protective clothing, high humidity and/or high wind speeds in the working areas. High or low temperature or humidity is important factors that affect working conditions in underground mines. In order to improve thermal comfort conditions, using convenient mechanical tools for reducing workload, organizing works better in order to reduce the heat stress in high temperature zones, ensure an adequate amount of drinking water that contains electrolytes for dehydration, protect workers against cold stress, hypothermia, and frost-bite and prevent workers' body temperature falls below 36^0 are necessary (DGOV, 2013).

In the study area, during site visits, it was seen that apparent temperature was slightly higher than the average. Workers tend to not to use PPE and dust masks. One reason of this is due to masks increase the apparent temperature and workers are not able to perform their tasks comfortably and this could lead to occupational accidents. Poor thermal comfort causes loss of concentration of workers and lead to occupational accidents. There is not sufficient information about thermal comfort during the accidents and because of that poor thermal comfort takes place as an undeveloped event in FTA.

Poor Ventilation (X24): Suitable quality and quantity of air should be ensured to maintain a safe and healthy environment in underground mining workplaces. Good ventilation both increases the thermal comfort conditions and air quality. In poorly ventilated underground mines, besides of dust and gas accumulation, poor air quality can lower the energy of the workers. Another obligatory directive according to the Regulation of OHS in Mining Workplaces is 'Directive of Ventilation'. Components that need to take place in ventilation directive are information about ventilation system; whether it is natural or forced, ventilation plan, conditions that can affect ventilation in the workplace, non-ventilated zones, air measurement intervals and zones, measurement of gasses, and precautions to be taken (MoLSS, 2013a).

During site visits general ventilation was sufficient, but in some zones the ventilation was poor and air velocity was relatively higher in some regions. In the accident data, there is not any information about the air and ventilation condition, thus, poor ventilation takes place as an undeveloped event in the FTA.

4.2.3 Human Error (A3)

Rushworth *et al.* (1999) stated in their study that in a research of the U.S. Bureau of Mines, about 85% of the mining accidents are human error-related (Patterson and Shappell, 2010). However, human error cannot be stated as the main factor of an incident. There are several underlying reasons behind human error and with all other errors, human error can be defined as the triggered factor of an accident. Dekker (2002) described human error in his study as a deficiency in the organization and should be approached as a system fault rather than blaming individuals that take part in the incident (Patterson and Shappell, 2010). Paul and Maiti (2008) indicated that job dissatisfaction, weak dedication to management, time pressure, procedure anxieties of workers' is important forecasters of occupational accidents and tend to commit violations (Lenné *et al.*, 2012).

There are some important responsibilities of the workers in underground mines. Firstly, if any unsafe condition is determined, workers should take corrective actions immediately. Also workers should not hesitate to get some help if needed. Every necessary equipment and material should be present in the working area, if they are not, then workers should take time to get these equipment. If there are any questions or worry about the roof control plan, these should be deliberated with supervisors. Since mine is a continuously changing environment, supervisors may not always be able to notice the changes. Also the information about changes in the roof and rib conditions should be discussed with co-workers. Another important concern is not to enter into abandoned or closed parts of the mine (MSHA, 2008).

Human error is examined as ‘Unsafe Acts (B7)’ and ‘Unsafe Conditions (B8)’. Unsafe acts are classified as errors, mistakes, and violations in the safety literature. Whereas unsafe conditions are generally due to managerial and supervisory situations. Unsafe acts and conditions are classified under human error and unsafe acts composed of misapplication of procedures, disuse or improper use of PPE and failure to take proper control measures, while unsafe conditions approach is on the basis of physiological and sociological situations of the workers. Unsafe acts and unsafe conditions cannot be examined separately since they affect human behavior together. Because of this reason, unsafe act and unsafe condition are combined with an AND Gate in the FTA as presented in Figure 4.1. Unsafe act and unsafe condition failure events are explained in detailed in the following sections. Also the frequency distribution and lost days related to each event of Human Error is given in Table 4.1. According to that table, Failure to Take Control Measures (X25), Accident Proneness (X35), and Poor Concentration (X38) have higher frequency rates. This shows that the effect of these events are higher to roof and rib fall accidents and preventive measures to them should be the top priority. Again the severity order of basic events are similar to frequency rate order that, the most severe events among human error are X38 (6.13%), X25 (6.10%), and X35 (4.66%).

4.2.3.1 Unsafe Act (B7)

In the study, Unsafe Acts are classified as, ‘Failure to Take Proper Control Measures (X25)’, ‘Equipment Related Failures (C4), and ‘Misapplication of Procedures (C5)’ as presented in Figure 4.10. All three events are connected with an OR-Gate to B7. Also, basic events under C4 and C5 are connected with OR-Gates. This means that, at least one of the occurrences of these basic events results in unsafe act.

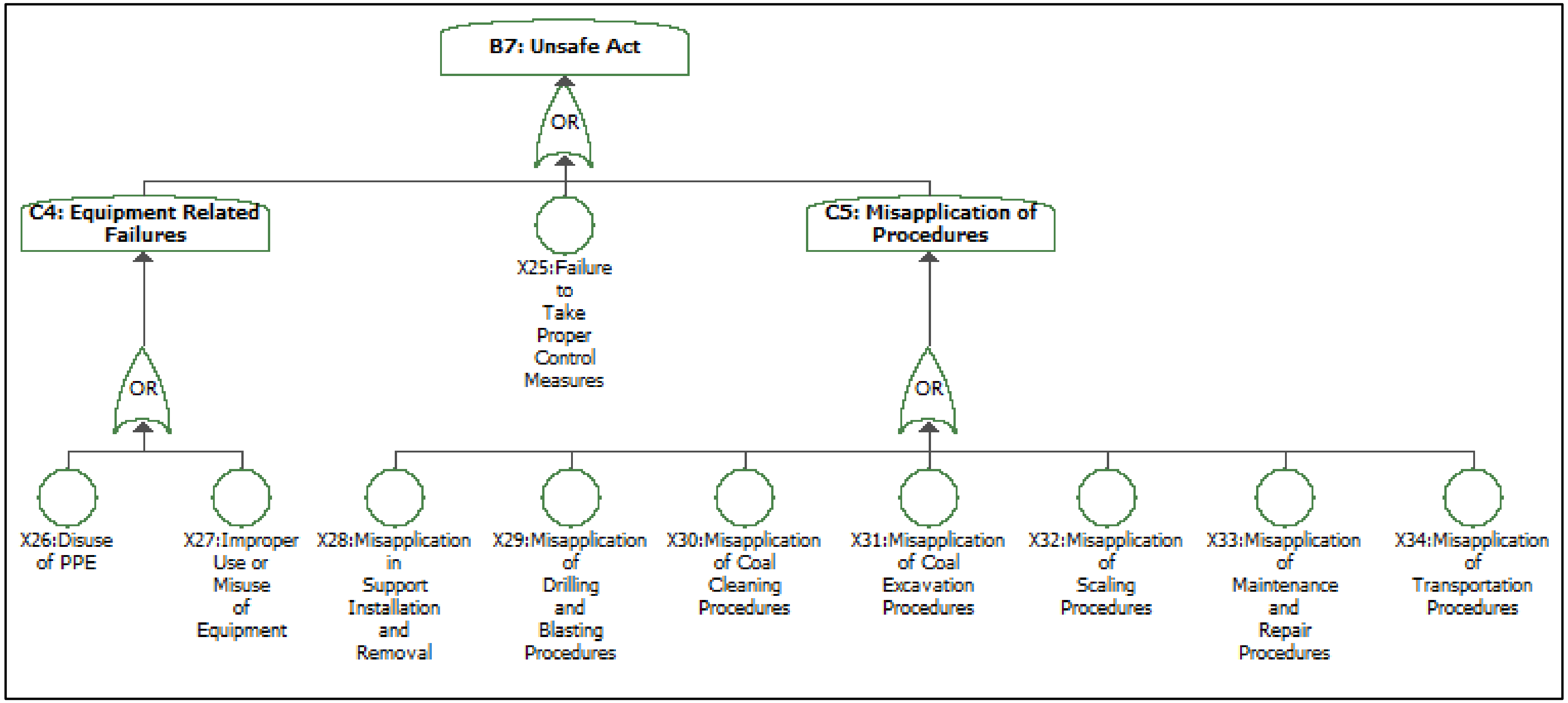


Figure 4.10 Fault Tree of Unsafe Act

***Failure to Take Proper Preventive Measurements (X25)*:** Safety in workplaces starts with being aware of the potential hazards and taking proper preventive measures. This awareness should start with management approach and transferred to lower organizational levels to engineers, supervisors, and then to front line workers. This situation is considered as a failure in the workplace and takes part in the FTA as inadequate occupational safety and health training under management error and again presented in inefficient inspections under engineering error. For human error, failure to take proper preventive measurements while or before work takes part under unsafe acts. This comprises accidents occurred due to workers' disregarding potential hazards while working or before starting the tasks. It is the employee's duty to inform potential hazards that they noticed in the workplaces to supervisors. They also have the right by legislations to avoid working if any situation occurs in the workplace that could jeopardize workers health and safety. This can be provided with proper training and safety culture. In this circumstance, if workers notice or pay more attention to these hazards some of these injuries could be prevented. There are 454 accidents related to this failure event which corresponds to approximately half of the occurred accidents (Table 4.1). It shows that, this event is one of the most important basic events and preventions among this case need to be taken with top priority.

Equipment Related Failures (C6)

Unsafe acts of workers include situations when workers make mistakes or errors about using the equipment. These equipment composed of PPE and equipment needed for tasks. This equipment related failures takes place as 'Disuse of Personal Protective Equipment' and 'Improper or Misuse of Equipment'.

***Disuse of Personal Protective Equipment (PPE) (X26)*:** Disuse of PPE as an unsafe act can only be valid if the proper training for PPE is given and all PPE are provided for workers. In the study area, provided PPE list is obtained from management and listed as:

1. Coveralls,
2. Reflective vests,
3. Long and short sleeved boots,
4. Safety caps with cap lamps,
5. Caps with hearing protection,
6. Nitrile gloves,
7. Protective glasses,
8. Respiratory protector, and
9. Dust masks.

According to the data, accidents related to not using PPE are generally head and eye injuries. During the study visits, it was seen that none of the workers use eye protection glasses. Also, it is known that coveralls and gloves are not able to protect from rock smashes. Furthermore, from the data it was seen that there were injuries due to not wearing head protection. Thus head and eye protection related accidents are considered under this failure event.

Improper Use or Misuse of Equipment (X27)**:** Improper use or misuse of equipment related accidents is present generally while drilling and blasting and scaling operations. This failure also occurs during maintenance and repair, coal cleaning and support installation and removal operations. In the study, it was found that 94 of the accidents occurred due to improper use or misuse of equipment.

Misapplication of Procedures (C7)

As it was mentioned before, procedural errors can occur as a result of both inadequate training and unsafe act of workers. Despite the fact that unsafe act's main reasons can be evaluated as an organizational error, it is still due to errors, mistakes or violations of workers. In the FTA these procedural errors are examined under seven basic failure events for seven different tasks (X28-X34).

Misapplication of Support Installation and Removal Procedures (X28)**:** When the data was examined, it was seen that there were 283 accidents related to misapplication of support installation and removal (Table 4.1). This shows that the majority of the support installation and removal accident's one of the important reasons is misapplication of procedure. Also majority of the procedural accidents is due to support installation and removal. These accidents occurred generally during crib installation and removal, rock falls from the supported part at the time support is installed, and during excavation for preparation of installation.

Misapplication of Drilling and Blasting Procedures (X29): Accidents during drilling and blasting mostly occurred because of wrong applications. Operators should both know how to use the drilling machines and how to avoid skin failures and rock falls from the drilled zone. There were totally 41 accidents related to wrong drilling and blasting (Table 4.1).

Misapplication of Coal Cleaning Procedures (X30): Coal cleaning implies cleaning coal away from face, drifts and roadways, and also it includes the general cleaning procedures in the mine. There were not many accidents occurred during coal cleaning, but about 35% of coal cleaning accidents occurred due to wrong procedure applications.

Misapplication of Coal Excavation Procedures (X31): Despite coal excavation injuries are the second major cause of roof and rib fall accidents, procedural misapplications of this task is comparatively less. Only 6% of coal excavation accidents occurred due to misapplication of procedures. This could be due to good procedural training and good perception or could also be due to lack of effective data.

Misapplication of Scaling Procedures (X32): It is mentioned in the management error that scaling training is not sufficient enough. This is again valid for procedural errors.

During scaling, operators should be able to avoid getting injured from skin falls and falling rocks and should apply scaling procedure better and safely.

Misapplication of Maintenance and Repair (X33): Similar to the coal cleaning procedure, again, there is a small number of accidents during maintenance and repair. However, also like coal cleaning procedure, 30% of these accidents occurred due to misapplication procedures.

Misapplication of Transportation Procedures (X34): There were 21 accidents occurred due to misapplications of transportation procedures. These accidents generally happened while carrying equipment manually or while assisting the experienced operator.

4.2.3.2 Unsafe Condition (B8)

Unsafe conditions define sociological and psychological circumstances that affect workers' behaviors in workplaces. This situation can be, lack of motivation, stress or burnout due to personal or family issues or due to mobbing in the work or could be due to inefficient salaries or long working hours or inexperience in the tasks performed.

Unsafe condition is evaluated as; 'Accident Proneness (X35)', 'Inexperience (X36)', 'Physical Unsuitability (X37)', 'Poor Concentration (X38)', and 'Lack of Motivation (X39)'. All of these basic events are connected with an OR-Gate (Figure 4.11). Events X37 and X39 are shown as undeveloped events and evaluated only in qualitative FTA.

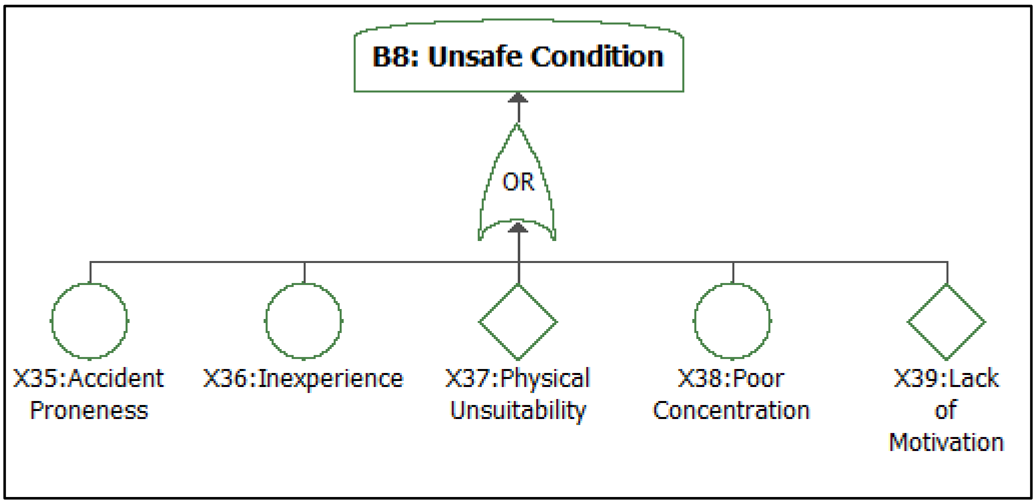


Figure 4.11 Fault Tree of Unsafe Condition

Accident Proneness (X35): Accident proneness theory explains accidents as a result of individuals' tendency to accidents. Accident proneness term was first introduced by Eric Farmer and Karl Marbe (1925) independently from each other and from that day forward, accident caused by individuals is referred as 'accident prone'. Farmer and Marbe (1925) tested accident prone workers in various industries like marine workers, army, bus drivers, shipwrights, mechanics, and electricians (Swuste *et al.*, 2010). Greenwood and Woods (1953) defined this phenomenon as, if a group of workers is observed in some period of time, it is generally seen that they suffered from some incidents and if these incidents are not taken seriously and individuals continue their tasks, it is probably detected that same individuals would get injured more than once (Greenwood and Woods, 1953).

In this study, accident proneness is considered as workers who got injured more than twice during 2003 – 2013 from roof and rib falls (other accidents apart from the roof/rib falls accident causes are not considered in accident proneness failure event). The reason of evaluating accidents that occurred more than twice to individuals is that, the first two of the accidents could be due to the nature of the mine or due to some other deficiencies, but it is assumed that if a worker injured more than twice just because of roof/rib fall accidents he/she could be accident prone.

When the roof and rib falls were examined according to the accident data, it was seen that there were totally 438 workers got injured from 879 accidents between the years 2003 and 2013. From these 438 workers, 383 of them are injured more than once due to roof collapse, skin falls, rock fall, and subsidence. In Table 4.4 numbers of injured workers and a number of repetitive injuries because of roof and rib falls are given. From the table it can be seen in the first raw that 160 workers got injured from roof and rib falls between the years 2003 and 2013, and it is seen from the last row of table that one of the workers got injured ten times only due to roof and rib falls.

Table 4.4 Number of Repetitive Injuries and Number of Workers Injured from Roof and Rib Falls

Number of Repetitive Roof and Rib Fall Injuries	**Number of Injured Workers**
1	160
2	115
3	55
4	27
5	10
6	5
7	4
8	4
9	1
10	1

<u>Inexperience (X36):</u> Between the years 2000 – 2007 in the U.S.A., 50% of the roof and rib fatality victims were experienced less than two years (MSHA, 2008). Siskind (1981) stated that accident rates in the first year of jobs are higher (Margolis, 2010). Also Mitchell (1988) found that workers younger than 25 have more tendency to get injured than older workers and he based this upon inexperience (Margolis, 2010). Age and experience phenomenon are generally considered together in examining health and safety. Ilmarinen (2001) stated that workers' perceptions improves as they age and gain experience, especially in the use of language and in progression of complex difficulties. He also stated that older workers have improved motivation and knowledge which comes with experience that helps to overcome inadequacies during their work life (Ilmarinen, 2001). However, in some studies, it was found out that experience does not show any variation between less experienced and experienced workers, only difference is that experienced workers tend to be more aware of the physical hazards but avoiding danger is more likely to be behavioral (Paul and Maiti, 2007).

Inexperience is considered under unsafe condition of human error. In Table 4.5, age and experience of workers who got injured from the roof and rib falls are given. It is seen that employees younger than 35 are more likely to get injured (85%). Also the majority of injuries occurred in the first five years (57%). In evaluating the FTA, workers less than three and less years of experience are considered under 'Inexperience' basic event. Inexperienced workers should work with less hazardous tasks until they learn tasks efficiently or work near experienced operators, at least for three years.

Table 4.5 Age and Experience of Injured Workers

Age	**Number of Workers**	**Percentage (%)**	**Cumulative Percentile (%)**
20 - 25	53	6.03	6.03
26 - 30	368	41.87	47.90
31 - 35	330	37.54	85.44
36 - 40	93	10.58	96.02
41 - 45	24	2.73	98.75
45 <	11	1.25	100.00

Experience (Years)	**Number of Workers**	**Percentage (%)**	**Cumulative Percentile (%)**
0 - 3	207	23.55	23.55
3 - 5	358	40.73	64.28
5 - 10	179	20.36	84.64
10 - 15	105	11.95	96.59
15 <	25	2.84	99.43
Unknown	5	0.57	100.00

Physical Unsuitability (X37)**:** Mining is known as one of the most hazardous jobs and it requires strength, health, and endurance. Not everyone's physical and health conditions are suitable for this job. The health of the workers needs to be examined detailed in medical examinations during pre-job period. During these examinations, physical suitability for the job need to be evaluated as well as health conditions. In the study, according to lack of information about the physical conditions of workers, basic event of 'Physical Unsuitability' only takes place in the qualitative FTA as an undeveloped event.

Poor Concentration (X38): One of the main reasons of accidents caused by workers is poor concentration. Lack of concentration can due to various reasons such as, depression, insomnia, alcohol or drug use, stress, family issues, long working hours, and fatigue. All of these reasons are conditions that specify worker's attitude and can trigger unsafe behavior.

Long working hours were discussed under management error. About alcohol and drug usage; in a survey applied in the study area, it has been seen that 62% of the workers are smoking and only 13% used alcohol (Durşen, 2015) and there was not any information about drug usage. In the same survey, 85% of the participants stated that they were married and 68% have two or more children.

In the study, accidents related to poor concentration of workers are evaluated from accident explanations, and other data and it has been found that 395 of the accidents are related to this basic event. This means that, nearly half of the accidents are related to poor concentration of workers. As it has been mentioned before, worker related-errors cannot be evaluated as a single error in an accident analysis, but when it comes together with other engineering and management errors, they have a triggering effect.

Lack of Motivation (X39): Like poor concentration, lack of motivation can be because of many different reasons. Accidents due to lack of motivation can be due to the low salary, mobbing, negative affectivity, job dissatisfaction, job dislike, low commitment to management *etc.* Negative affectivity term is used for situations like negative emotional states of workers. Hansen (1989), and Iverson and Erwin (1997) stated that people with negative affectivity tend to have distraction impairments which make them more prone to accidents and injuries. Also, Judge (1993) suggested that studies have shown that negatively affected workers are not tending to check their work environment. Maiti *et al.* (2004) stated that negative affectivity is one of the major problems in underground coal mines (Paul and Maiti, 2007). Due to lack of data about psychological situations of the workers at the time they injured, lack of motivation cannot be quantitatively analyzed in the fault tree. Thus, it only takes part as an undeveloped event in the qualitative part of the study.

4.3 Quantitative Fault Tree Analysis

Intermediate events and basic events are all described in the Qualitative FTA part of this chapter. In the quantitative fault tree analysis, undeveloped events are removed since they cannot be analyzed quantitatively. Also, in the qualitative analysis section, events are mentioned elaborately. In the quantitative FTA, in order to calculate the probabilities more accurately, it is more efficient to use less basic events. In order to do that, some of the events are combined under the same basic events. For example, Insufficient Roof Support (X4), Deterioration or Distortion of Support Elements (X5), Insufficient Temporary Face Support (X6), are combined under Insufficient Face and Roof Supports (XS) basic event. This event includes all accidents happened due to support system failures. Also similarly, Inadequate Training of Scaling (X11), Support Installation and Removal (X12), Coal Excavation (X13), Drilling and Blasting (X14), and inadequate training of other operations (X15) are combined under Inadequate Job Training (XE) event. All incidents happened due to procedural training deficiencies are evaluated under XE. Lastly, X28 – X34 are combined under Procedural Errors (XP). All accidents that includes procedural errors of workers are evaluated under XP basic event.

4.3.1 Formation of Fault Tree Analysis

While analyzing the quantitative fault tree, the aim is firstly to make predictions about failure times of each event by fitting a statistical distribution. The distribution of the data set can be used to estimate the probability of failure of the system at a specific time and the mean life. In order to accomplish that, firstly failure data of the system are gathered, which is the accident dates. Then a lifetime distribution is fitted to each event. Lastly, general plots and results that estimate the probability of failures and mean life of the system are generated.

Quantitative analysis was conducted using ReliaSoft Blocksim-7 and Weibull-7 programs. Blocksim-7 software was used for evaluating fault tree of the system, in order to understand the relationships between these failure events. Weibull-7 software was used to calculate the distributions and of the events included in the system.

There are totally 3 primary events, 9 secondary events, and 19 basic events in the quantitative version of the fault tree analysis as presented in Figure 4.12. Primary events A1, A2, and A3 are combined with Voting Gate (2/3) as explained in Section 4.2. Top event 'Roof and Rib Fall Accidents' is shown with 'T' in the fault tree. Other events under these major events are combined with AND, OR, and Voting gates similarly as explained in Section 4.2. Voting-Gate under A2 is shown as 2/3, since basic events under B6 are undeveloped events cannot be analyzed quantitatively. Also other undeveloped events are separated from the tree and as a result, there are 5 basic events under A1, and 7 basic events each for A2 and A3. Each of these major event's fault trees for quantitative analyses are given in the following sections.

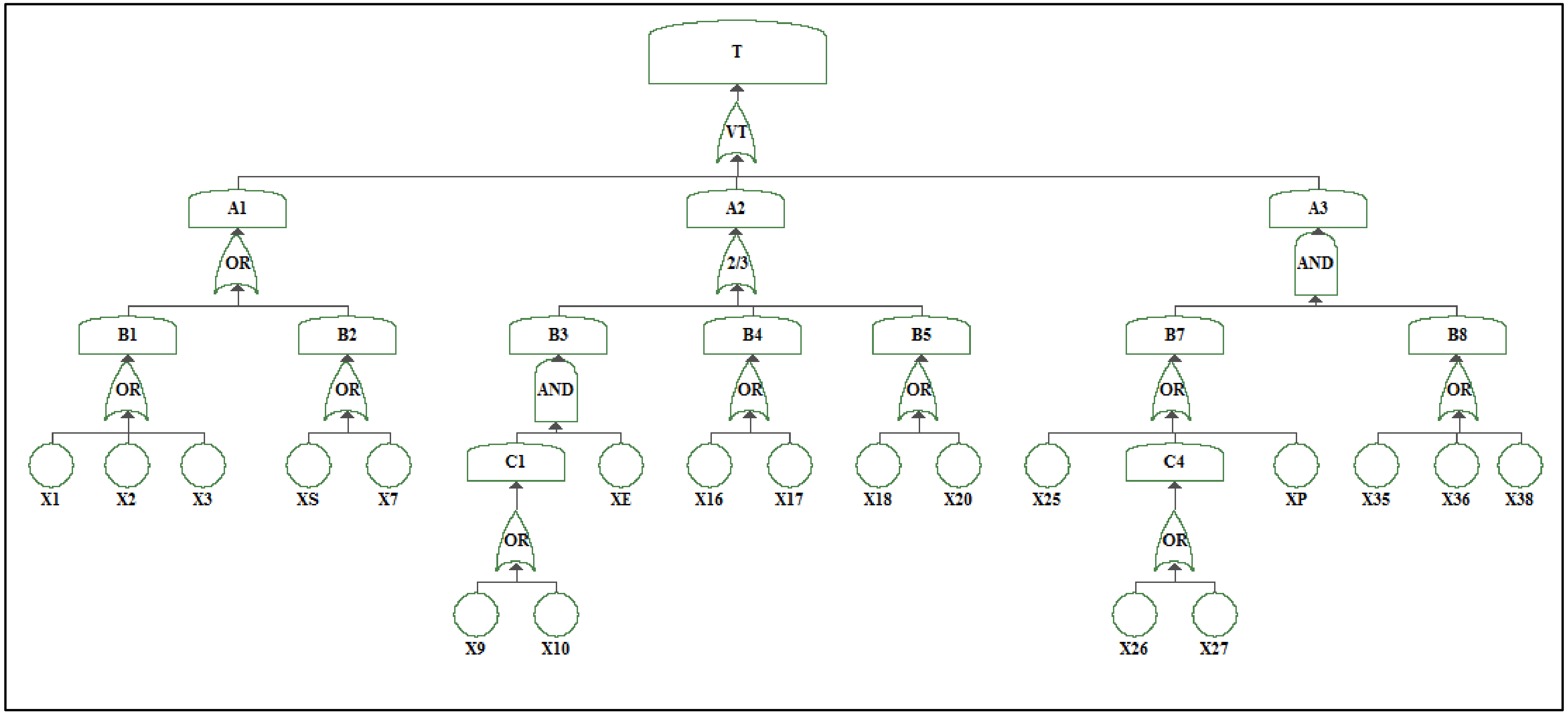


Figure 4.12 Fault Tree for Quantitative Analysis of Roof and Rib Fall Accidents

4.3.2 Testing the Randomness of the Data

The data used in the analysis is the time between failure data, i.e. the time passed after one failure until another failure occurs. Before determination of the distributions, the data need to be tested for randomness. The randomness analysis of the data was performed via MATLAB Software using 'runstest' function. This test checks whether or not the number of runs is the appropriate number of runs for a randomly generated series. The function returns a test decision for the null hypothesis (H_0) indicates the data come in a random order.

In the test, a run is one or more consecutive data point that are in the same direction. The runs test is based on the number of runs up or down (increasing or decreasing). Small number of runs indicates a trend, while a large number of runs shows an oscillation. If the consecutive data points have the same value, the former value is discarded from the test.

The null (H_0) hypothesis determines the randomness of the sequence. The "p-values" obtained from the test specifies the probability of observing the detected value under the null hypothesis. The range of the "p-value" is between 0 and 1. The small "p-values" cast doubt on the validity of the null hypothesis which concludes the randomness of the data. With 99% of confidence intervals, limit p value is 0.01.

Results of the runs test of each basic event are presented in Table 4.6.The first column in the table shows the p-values of each basic event and since all these values are higher than 0.01, all events are continuous and randomly distributed. The second column gives information about data number of each basic event. Also, the results of the runs test for each event and the MATLAB code are presented in Appendix A in Figures A.1-A.19. Representative examples for the runstest for events X3 and X20 are given in Figure 4.13 and Figure 4.14 respectively. X20 has a p value of 0.967, which is greater than 0.01, which means it is randomly distributed. Also the values shown on the top of The Run Chart are the outliers. Likewise, X3 has a p value of 0.386, which is also randomly distributed.

Table 4.6 Results of Runs Test for Each Basic Event

	P-Values	**# of data**
X1	0.075700171	355
X2	0.206958055	271
X3	0.385654660	620
XS	0.692909515	675
X7	0.024225405	797
X9	0.650423256	175
X10	0.085845884	742
XE	0.026659348	792
X16	0.043779240	262
X17	0.654481436	66
X18	0.010101829	879
X20	0.966613470	93
XP	0.630466582	530
X25	0.243913747	454
X26	0.638394500	162
X27	0.836031441	94
X35	0.165314478	430
X36	0.886924383	207
X38	0.917626326	395

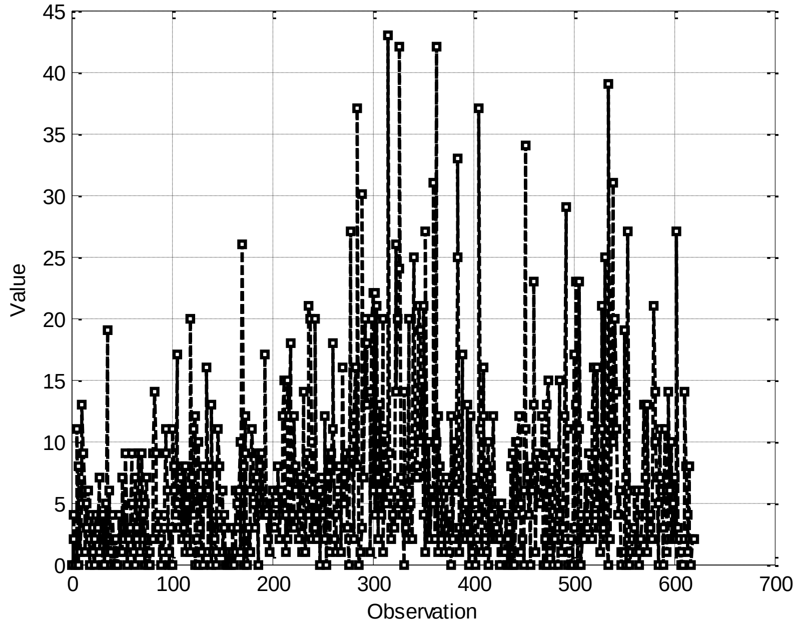


Figure 4.13 Run Chart of Basic Event X3: Failure to Control Preventive Safety Measures

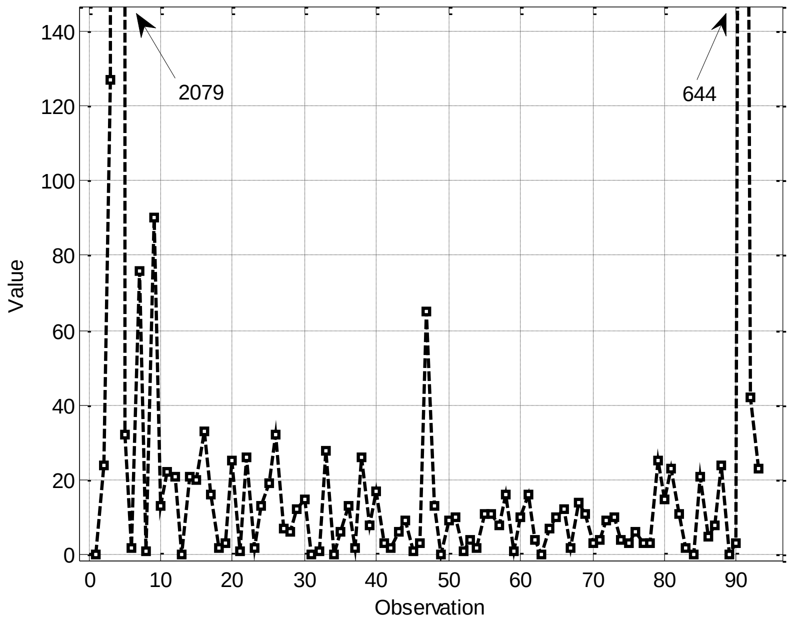


Figure 4.14 Run Chart of Basic Event X20: Giving Hazardous Tasks to Inexperienced Workers

4.3.3 Probability Distributions of the Failure Events

Since in the test of randomness of the data all events were found as randomly distributed, probability distributions of the failure events could be evaluated. Probability distributions of all events were evaluated using ReliaSoft Weibull++7 Software.

The data presented to the software is the accident dates of the each event. The unit of the time is 'days'. Weibull++7 software calculates the distribution of each event using the time between failures. In other words, the data that input to the program is the days between two consecutive accidents. The results of distribution analysis of each event are given in Table 4.7. Event distributions were found as Weibull 2-P and 3-P distributions.

Table 4.7 Distribution Parameters of Events

Event	Distribution	Distribution Constants		
		β	η	γ
X1	Weibull 3P	0.845	10.361	0.808
X2	Weibull 3P	0.976	14.750	0.808
X3	Weibull 3P	0.946	6.379	0.720
XS	Weibull 3P	0.907	5.766	0.765
X7	Weibull 3P	0.930	4.945	0.735
X9	Weibull 3P	0.824	20.293	0.899
X10	Weibull 3P	0.944	5.418	0.718
XE	Weibull 3P	0.925	5.001	0.733
X16	Weibull 3P	0.833	13.843	0.858
X17	Weibull 3P	0.892	57.626	0.180
X18	Weibull 3P	0.937	4.504	0.733
X20	Weibull 3P	0.834	13.116	0.768
XP	Weibull 3P	0.880	7.210	0.740
X25	Weibull 3P	0.976	8.836	0.728
X26	Weibull 3P	0.832	22.245	0.875
X27	Weibull 2P	0.930	41.540	0
X35	Weibull 3P	0.960	9.043	0.700
X36	Weibull 3P	0.785	6.442	0.850
X38	Weibull 3P	0.810	9.286	0.770

The probability density function (PDF) is a mathematical function that describes the distribution. The PDF can describe mathematically or on a plot where the x-axis represents time (Reliasoft Corporation, 2015). The Weibull distribution is one of the most widely used lifetime distributions. It is a multipurpose distribution that can assume the characteristics of other types of distributions, based on the value of the shape parameter, β. There are 3-parameter, 2-parameter, and 1-parameter Weibull distributions (Reliasoft Corporation, 2015). Events in the study have Weibull 3-P and 2-P distributions.

3-parameter Weibull probability density function (PDF) is presented in Equation 5.

$$f\ (t) = \frac{\beta}{\eta}(\frac{t-\gamma}{\eta})^{\beta-1}e^{-(\frac{t-\gamma}{\eta})^{\beta}} \quad (1)$$

where: $f(t) \geq 0,\ t \geq 0\ or\ \gamma$

$\beta > 0,\ \eta > 0$

$-\infty < \gamma < +\infty$

and: η = scale parameter,

β = shape parameter (or slope)

γ = location parameter

The 2-parameter Weibull PDF is obtained by setting γ =0 (Reliasoft Corporation, 2015).

Shape parameter β, is also the slope of the regressed line in a probability plot. In the study, all of the shape parameters are between 0 and 1, and close to 1. Shape parameters for 0 < β ≤ 1 suggest a failure frequency of high at the start and decrease continuously.

For 0 < β ≤ 1;

As t → 0 (or γ), f(t) → ∞,

As $t \rightarrow \infty$, $f(t) \rightarrow 0$,

$f(t)$ decreases monotonically and is convex as it increases beyond the value of γ (Reliasoft Corporation, 2015).

4.3.4 Fault Tree Analysis of the System

In this section, fault tree analysis was applied including all events that cause roof and rib fall accidents. Firstly, the minimal cut sets were obtained using Boolean algebra, which was explained in Chapter 2. Minimal cut set is the smallest combination of failure events, which cause the top event to fail if all of the elements in the cut tree fail. Fault trees can contain a finite number of cut sets. However, cut sets are generally evaluated in order to simplify the tree if there is repetitive basic events (Vesely *et al.*, 1981). As can be seen from Figure 4.12, there is not any repetitive basic event in the fault tree. Thus, minimal cut sets could not be used to simplify the tree. The simplest form of the fault tree is the one shown in Figure 4.12. However, even if the tree cannot be simplified, this analysis composed of 264 minimal cut sets which are given in Appendix B. 96 of these cut sets include of 5 events, 88 include 4 events and 80 include 3 events.

In analyzing quantitative fault tree, firstly the mean time of the system was evaluated. Mean time is the expected or average time-to-failure, in other words, it is the mean time to failure (MTTF). The mean time of the system was found as 3.731 days, which means that there could be roof and rib fall accidents occurred in the mine in average of approximately every 4 days.

According to that mean time, probability of failure and reliability of the system was calculated. Probability of failure means the probability that the system will fail at a particular point in time. Probability of failure is also known as unreliability and it is the reciprocal of the reliability. It was found from the calculation that, the system has a 59.39% of probability to fail at 3.731 days and 40.61% probability of not to fail. Calculation results are given in Figure 4.15.

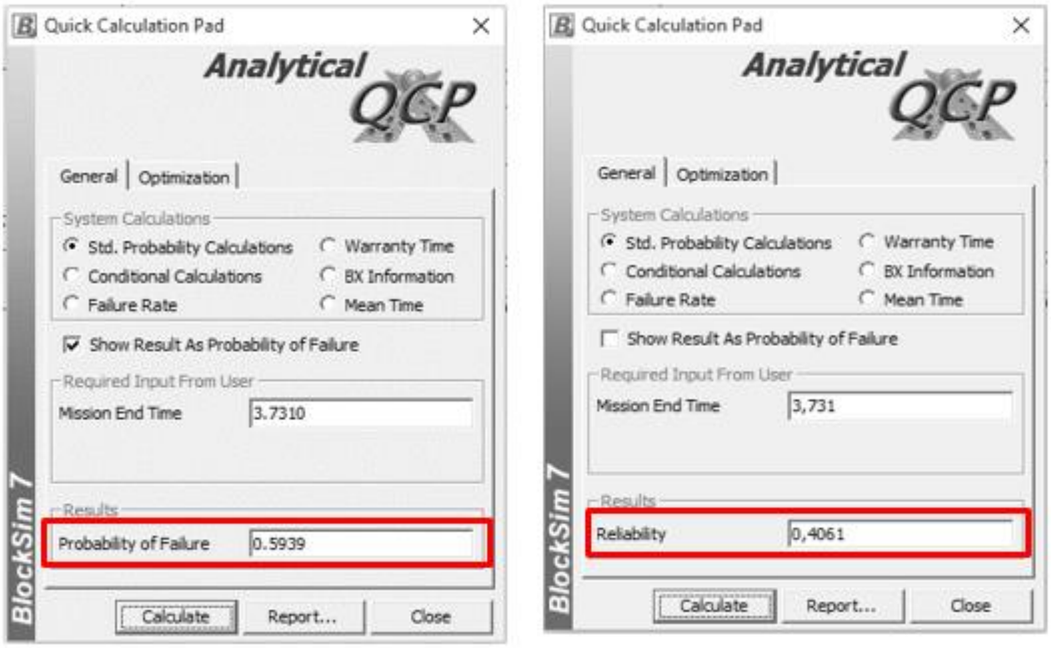


Figure 4.15 Probability of Failure and Reliability of the System in 3.731 Days

The Weibull unreliability function is represented by;

$$F\ (t) = 1 - e^{-(\frac{t-\gamma}{\eta})^{\beta}} \tag{2}$$

Reliability, which is the reciprocal of the probability of failure is shown as;

$$R\ (t) = 1 - F(t) \tag{3}$$

According to the mean time of the system, probability of failures of each basic event were found and presented in Table 4.8 in a descending order. Also, the reliability values were given. These values represents the independent probability of failures of each event at 3.731 days. For example, X18-Insufficient Risk Assessment related accidents tend to occur with 49.50% probability at 3.73 days.

Table 4.8 Probability of Failure and Reliability of Each Basic Event for 3.73 Days

Block	Probability of Failure	Reliability	Block	Probability of Failure	Reliability	Block	Probability of Failure	Reliability
X18	0.4950	0.5050	**X3**	0.3884	0.6116	**X20**	0.2510	0.749
X7	0.4661	0.5339	**XP**	0.3694	0.6306	**X16**	0.2367	0.7633
XE	0.4638	0.5362	**X38**	0.3272	0.6728	**X2**	0.1862	0.8138
X10	0.4372	0.5628	**X35**	0.2953	0.7047	**X9**	0.1777	0.8223
XS	0.4215	0.5785	**X25**	0.2945	0.7055	**X26**	0.1645	0.8355
X36	0.4125	0.5875	**X1**	0.2905	0.7095	**X27**	0.1009	0.8991
						X17	0.0799	0.9201

The Probability Density Function (PDF) vs. time plot of the system is given in Figure 4.16 for a period of one month (30 days). Since the variables are continuous random variables, the exact probability at an exact time cannot be evaluated from that plot. Rather, probability in a given interval can be evaluated. The probability density function vs. time plot gives the approximate value of the probability at a given time.

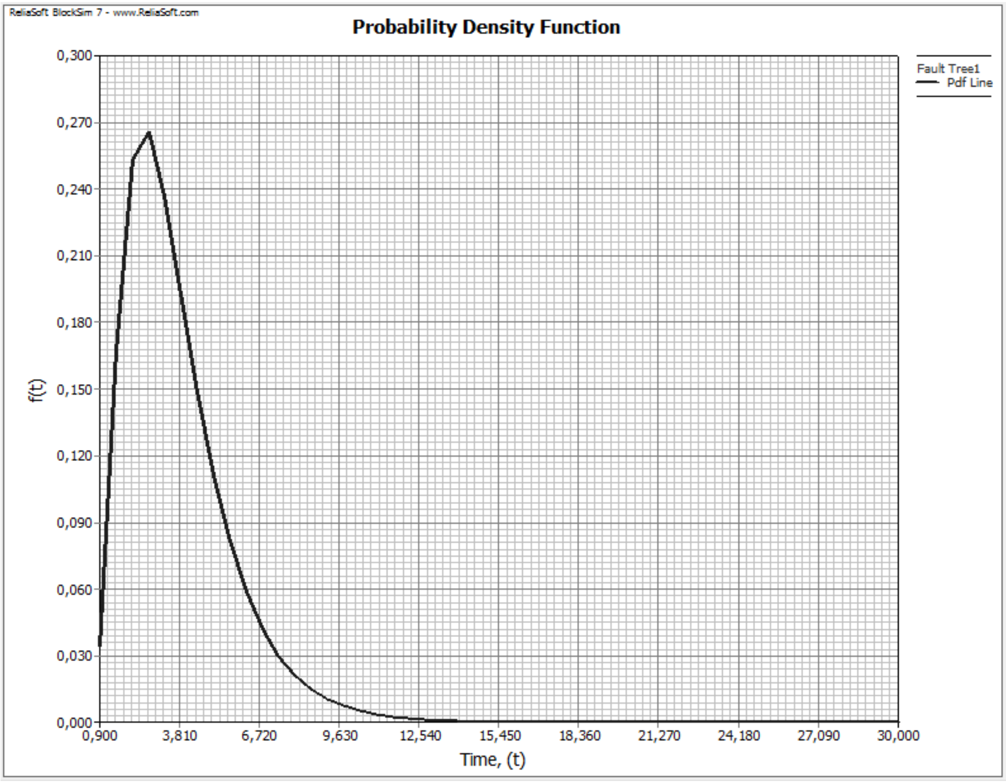


Figure 4.16 Probability Density Function vs. Time

From the PDF plot it is seen that, f(t) approaches to 0 after approximately 20 days. It can be interpreted that the probability of the failure becomes constant after about 20 days. In order to identify this phenomenon, the probability of failure vs. time plot was evaluated and presented in Figure 4.17.

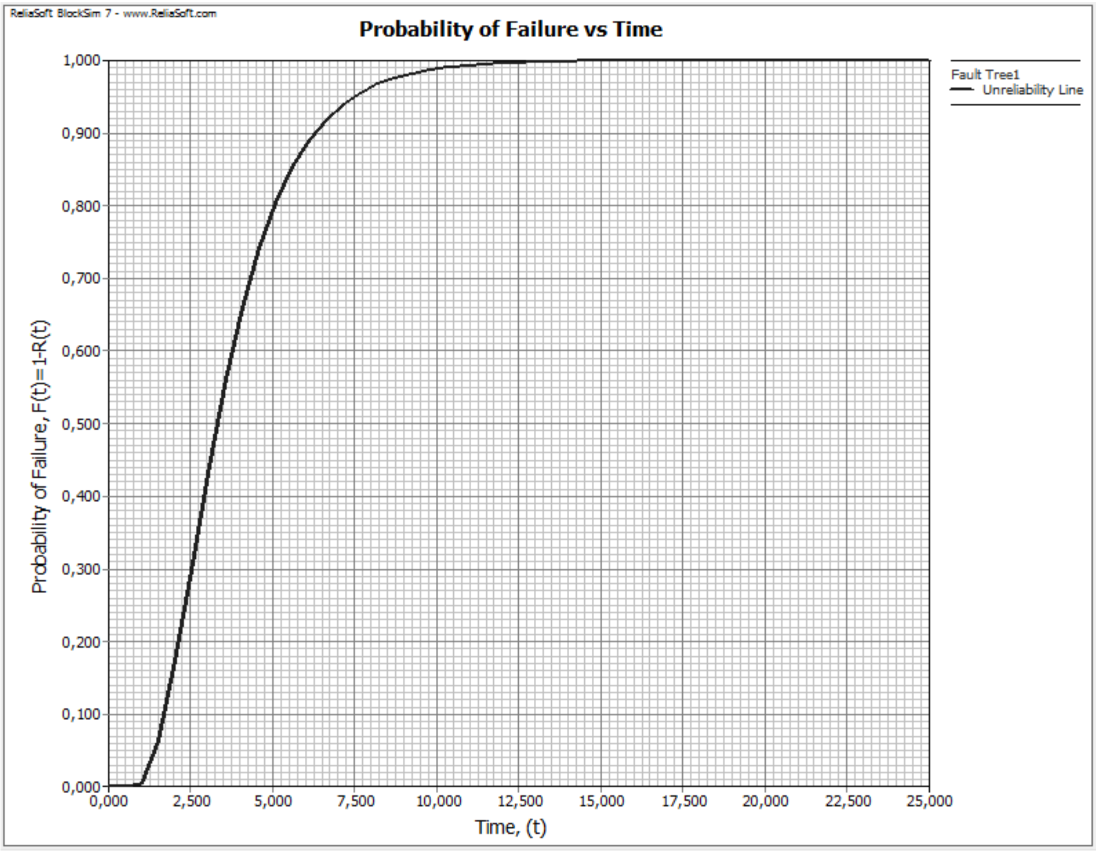


Figure 4.17 Probability of Failure vs. Time

From Figure 4.17, it is seen that probability of failure approaches to 1 at 20 days. For exact calculation, probability of failures for 17, 18, 19, and 20 days were calculated separately and the results were shown in Figure 4.18. It is seen from these calculations that the probability of failure is exactly 1 at 20 days. These results coincide with the PDF of the total system.

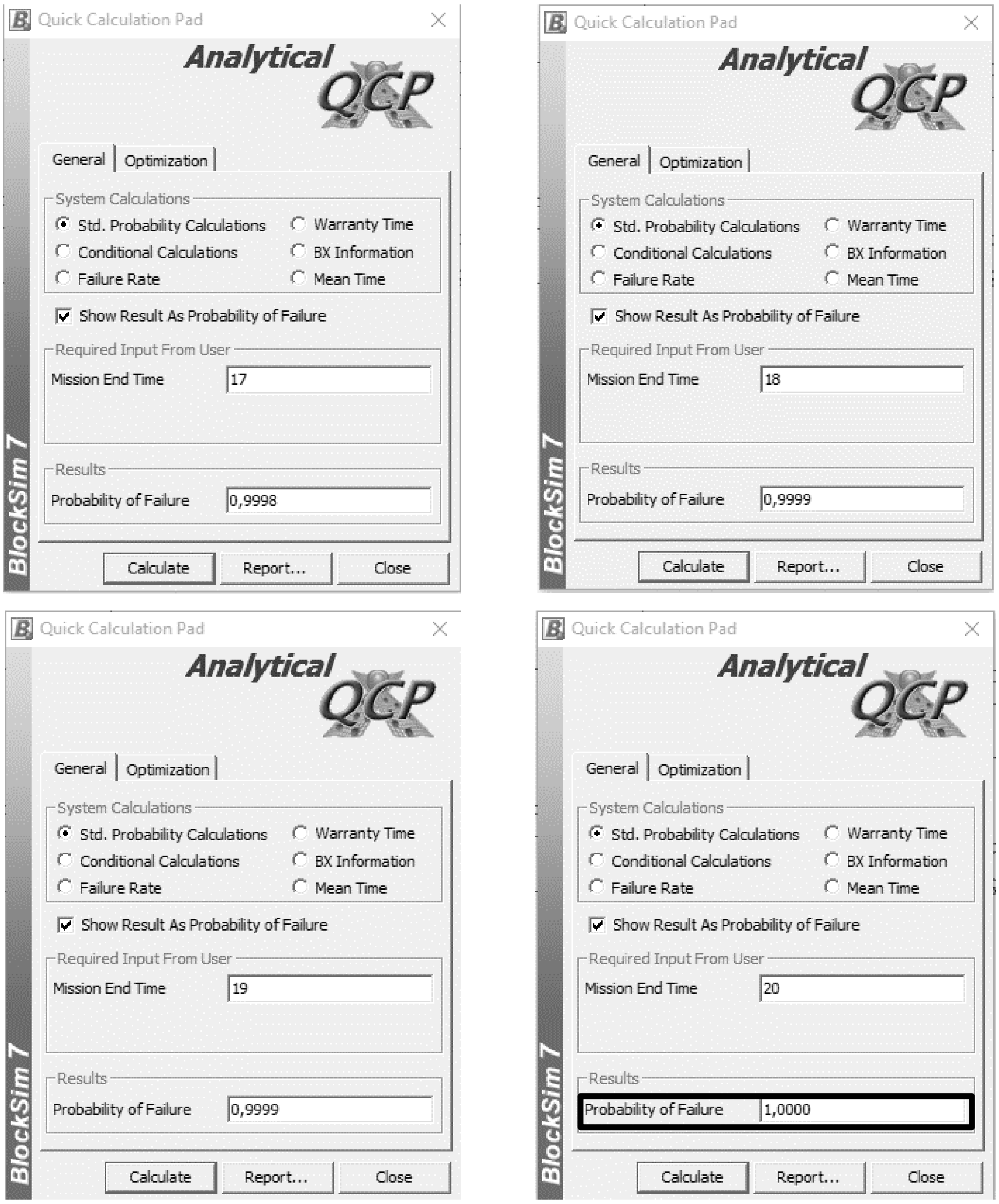


Figure 4.18 Probability of Failures for 17, 18, 19, and 20 days

In the light of this information, probability of failure vs. time plot of all basic events for a 20 day period is presented in Figure 4.19. The probability of failures of each event at 20 days is also given in Table 4.9.

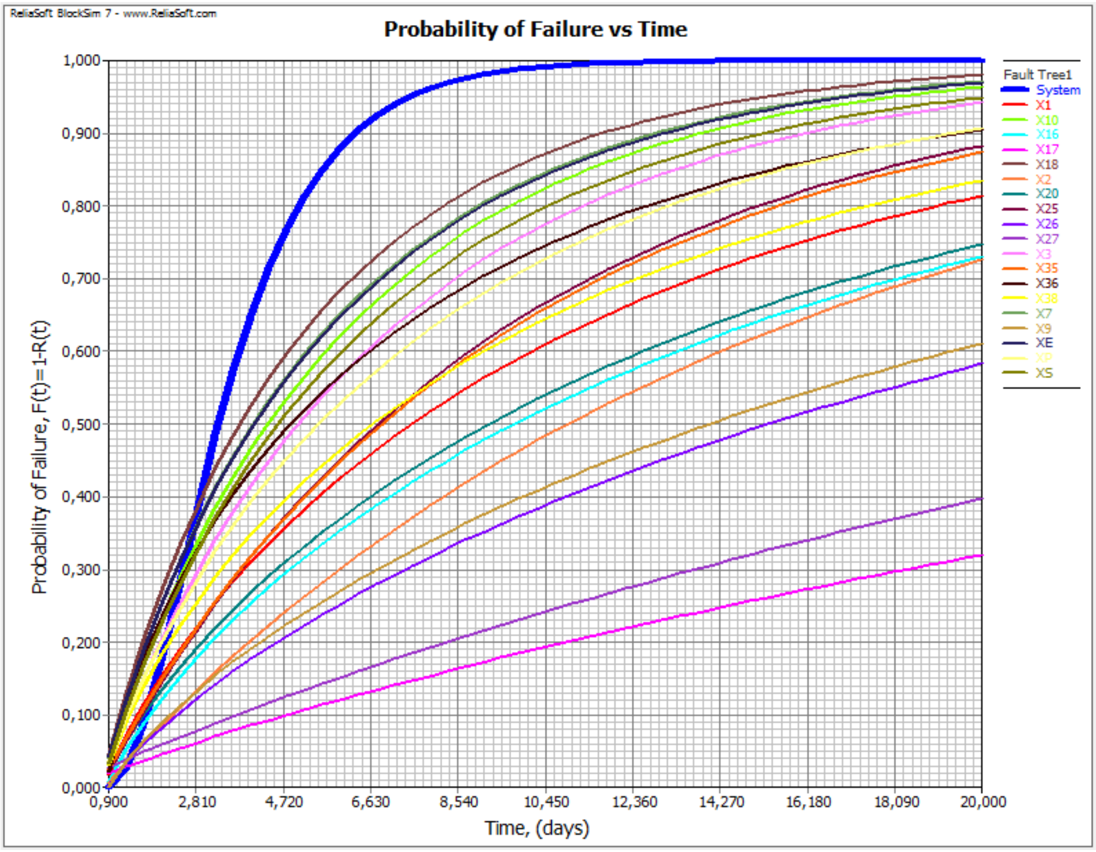


Figure 4.19 Block Probability of Failure vs. Time Plot

Table 4.9 Probability of Failure and Reliability of Each Basic Event for 20 Days

Block	Probability of Failure	Reliability	Block	Probability of Failure	Reliability
X18	0.9798	0.0202	**X38**	0.8352	0.1648
X7	0.9710	0.0290	**X1**	0.8143	0.1857
XE	0.9692	0.0308	**X20**	0.7475	0.2525
X10	0.9637	0.0363	**X16**	0.7301	0.2699
XS	0.9493	0.0507	**X2**	0.7255	0.2745
X3	0.9419	0.0581	**X9**	0.6108	0.3892
XP	0.9069	0.0931	**X26**	0.5829	0.4171
X36	0.9048	0.0952	**X37**	0.3976	0.6024
X25	0.8824	0.1176	**X17**	0.3203	0.6797
X35	0.8740	0.1260			

Figure 4.19 demonstrates independent distribution of each event with the system. Even though some of the basic events do not approach to 1 during that given period of time, the system's probability of failure approaches to 1 in 20 days. The events with the highest probability of failure in 20 days were found as, Insufficient Risk Assessment (X18), Improper Additional Roof Supports (X7), and Inadequate Job Training (XE). When the probability of failures at 20 days compare to the probability of failures at 3.731 days, it was observed that, significance order according to probability of failures changes.

In order to evaluate the most important events in the system, the reliability of importance and the static importance of failure events should be examined. Reliability importance is used to identify the relative importance of each event in a system with respect to the overall reliability of the system. The reliability importance I_R, of component 'i' in a system of 'n' components is given by Leemis as (Reliasoft Corporation, 2015);

$$I_{R_i}=\frac{\partial R_S}{\partial R_i} \tag{4}$$

In Equation 4:

R_S is the system reliability,

R_i is the component reliability

Reliability importance is a measure of how much impact each component has on the overall reliability of the system. It shows that the events that have the greatest effect on the system reliability. The events that most influence the system can be found using reliability importance and preventive measures can be taken amongst them firstly. In complex fault trees, the value of the reliability importance depends both on the component's reliability for the system and its position in the fault tree. In order to understand the reliability importance (RI) of all events in the system, reliability importance vs. time was plotted and presented in Figure 4.20. RI vs. time plot shows the reliability importance of the components over time.

It can be seen from RI vs. time that, the events with highest reliability importance were found to be X19, XP, X20, X28, and X39. The event with the highest probability of failure, X21, ranked ninth amongst all failure events in the reliability importance analysis. Also in Figure 4.19 and Table 4.9, it can be seen that the event with the lowest probability of failure rate, X20, ranked third in the reliability of importance graph. In order to define the reliability importance of components at a specific time, the static RI plot is evaluated.

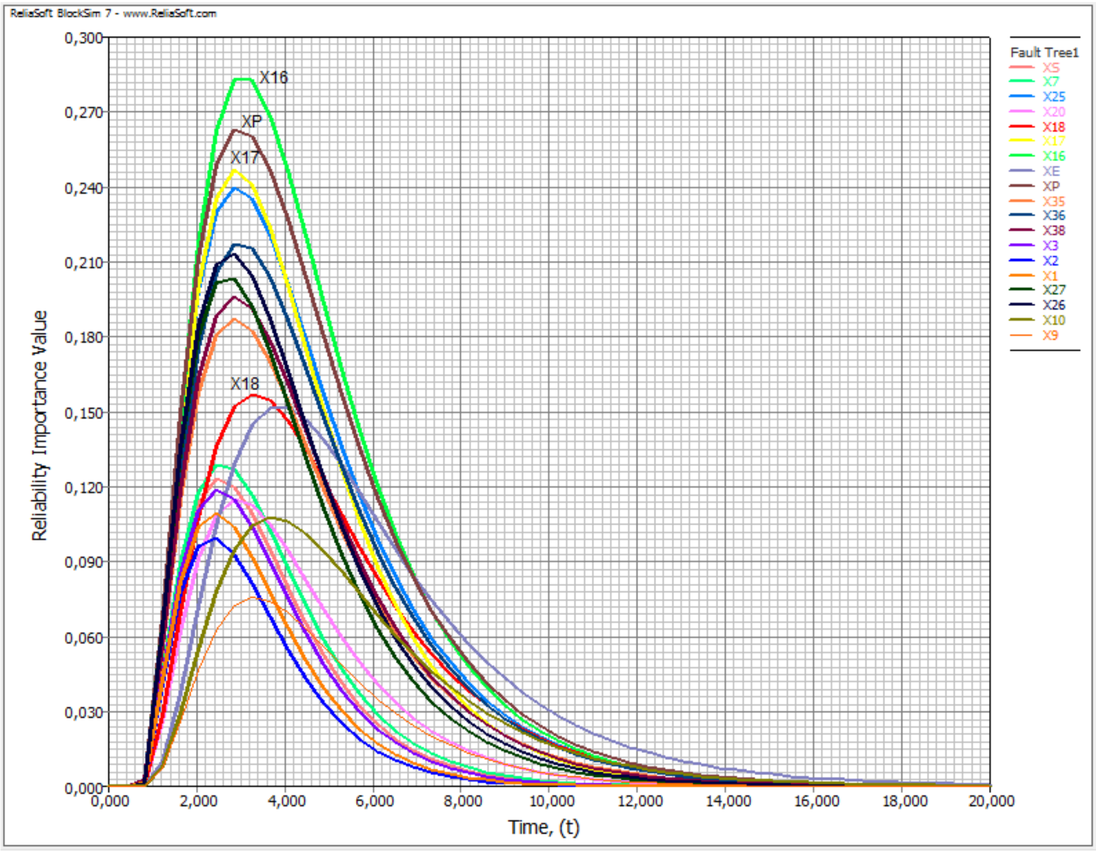


Figure 4.20 Reliability Importance vs. Time Plot

Static reliability importance of all events for the man time which is 3.731 days are given in Figure 4.21. The most significant event here is also found as X16 (Improper PPE), and followed by XP (Procedural Errors), X17 (Improper Tools), X25 (Failure to Take Control Measures), and X36 (Inexperience). Also, the most reliable event was found as X2 (Inefficient Support Inspections) at this specific time. Color scale in that graph represents the independent probability of failures of each event, which means that, as the block becomes red, probability of failure increases.

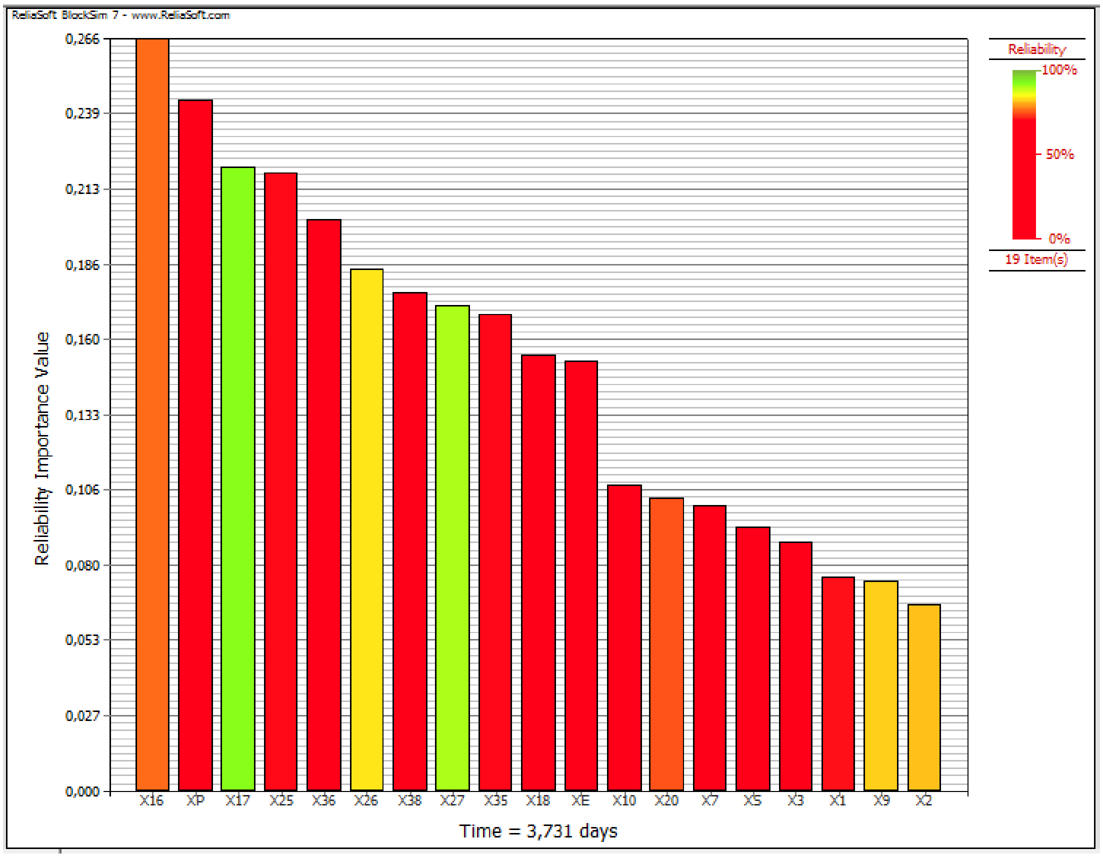


Figure 4.21 Static Reliability of Importance for 3.731 days

Static reliability of importance graph gives the events that need improvement in a descending order. According to this information, mean time and probability of failure of the system was calculated again by eliminating the first five events with the highest reliability of importance. The results of this analysis showed that MTTF of the system increase to 6.739 days and also the probability of failure of the system becomes 1 in

44 days. It means that, if preventive measure were taken primarily for the first five events by means of reliability of importance, system's reliability would increase and also, the mean time of the system would increase nearly twice as much of the first mean time. Also the time passed for all system to be failed increases more than twice when compared to the first case. Events with the highest static reliability importance for the new mean time were found as XE, X26, X27, X10, and X18, as presented in Figure 4.22.

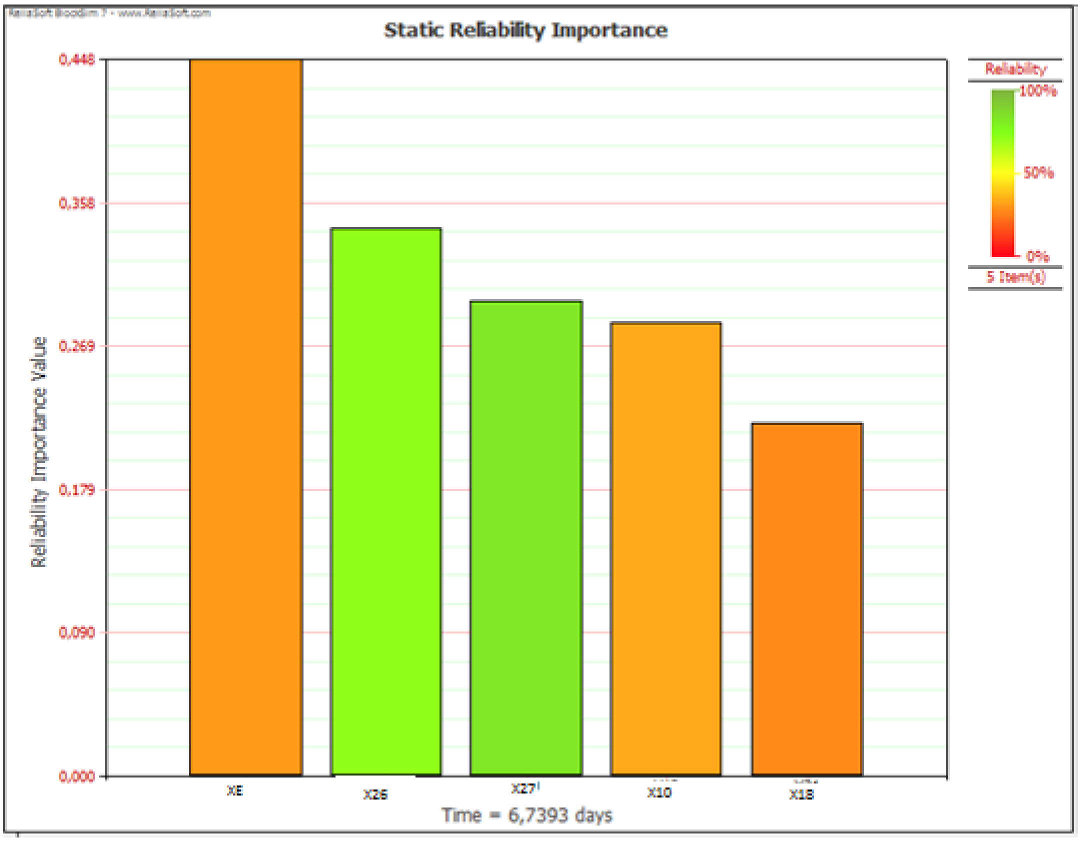


Figure 4.22 Static Reliability Importance for the New Mean Time

If the necessary preventive measures were taken for the first five events in terms of static reliability importance (X16, XP, X17, X25, X36), and they could be prevented. The next step must be taking the preventive measures for the events shown in Figure 4.22. Then the events that lead roof and rib fall accidents should be revised in the particular workplace and the analysis should be repeated accordingly.

4.4 Results and Discussion

In the FTA, firstly, the qualitative study was performed. The qualitative fault tree was formed according to the failures detected in the beginning of the study. Since the fault tree is a deductive method, reasons of roof and rib fall accidents were evaluated from top to bottom. Firstly, primary failure events were found as Engineering/Supervisor Error (A1), Management Error (A2), and Human Error (A3). Along with this primary events, there are 39 basic events detected as a result of fault tree. The frequency rate of each event according to their contribution to each accident was evaluated. Within these 39 basic events, eight of them (X8, X19, X21, X22, X23, X24, X37, and X39) were identified as undeveloped events, which cannot be further analyzed due to the lack of efficient accident data about these events.

Severities of the accidents were also generated within the data. The effect of each event by means of severities was also evaluated from lost days of each accident per total lost days per total number of workers. During 2003 to 2013, there were 10,299 lost days only due to roof and rib fall accidents in the research area. When the severities are analyzed on the basis of basic events of the fault tree, it is seen that top three most severe events are X18- Insufficient Risk Assessment, X7- Improper Additional Roof Supports, and X10 - Poor Safety Culture. Table 4.2 shows severities according to each basic event in a descending order. It is important to state that these severity rates were evaluated separately for each event. High severity rates mean, these accidents have downsides of both to employee health and safety and have bad economic impacts to the workplace. In further studies, the impact of lost days of the economy of the workplace could be examined.

In quantitative analysis, some of the basic events were gathered together in order to make calculations efficiently. X4, X5, and X6 were combined under Insufficient Face and Roof Supports (XS), X11-X15 were combined under Inadequate Job Training (XE), and X28-X34 were combined under Procedural Errors (XP).

The next step is a distribution fitting for each component. In order to evaluate the distributions, firstly data needed to be tested for randomness. After all the data was tested via MATLAB by using runstest function, it was found that data were randomly distributed and event distributions were found as Weibull 2-P and Weibull 3-P.

According to the distributions, using BlockSim 7 software fault tree analysis was executed in order to find the mean time of the system, probability of failures of both the system and each event independently, and also the most effective events in the causation of roof and rib fall accidents.

Mean life of the total system was found as 3.73 days, which means that, approximately in every 4 days, a worker got accidents from roof and rib falls in the study area. Probability of failure of the system according to that mean time was calculated as 59.39%.

Then block probability of failures were evaluated independently for each event. The events with the highest failure probabilities were found as X18, X7, XE, X10, and XS, which gives similar results with frequency rates. However, since these were the independent values of each event, the effect of these events to the system was evaluated using reliability importance.

Reliability importance with time plot gives the result of most important events as X16 – Improper PPE, XP – Procedural Errors, and X17 – Improper Tools for mean time of the system (3.731 days). It can be said that, if the top priority is given to those events and preventive measures were taken firstly for these top events, expected time of the system would increase. In accordance with that information, reliability importance was calculated without these five most important events, by making the assumption of the necessary prevention methods was applied to these events and they could have been prevented. Results showed that the mean time of the system increased nearly as twice of the mean time, and found as this time, approximately in every 7 seven days, roof and rib fall accidents occurred.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main conclusions drawn from this study is listed as:

- In TTK- Amasra underground coal mine, there were 879 accidents related to roof and rib fall accidents in the years between 2003 and 2013. Four of these accidents resulted in fatalities and the rest resulted in injuries. Also, these accidents have an outcome of 10,299 lost days.

- Most of the roof and rib fall accidents occurred during support installation and removal (45.51%) and coal excavation (27.19%) procedures.

- There were 39 basic causes determined as a result of the qualitative FTA, and major causes of roof and rib fall accidents were determined as Management Error, Engineering/Supervisor Error, and Human Error.

- Most frequent events were found as Insufficient Risk Assessment (10.97%), Improper Additional Roof Supports (9.95%), Poor Safety Culture (9.26%), and Failure to Control Preventive Safety Measures (7.74%). Severity rates showed a similarity with the frequency order of the events. Insufficient Risk Assessment (X18) event had the highest severity with 11.16 %. The reason of it is that this basic event affects all of the accidents.

- Minimal cut sets of the system were evaluated via BlockSim 7 software. 264 minimal cut sets were found and 96 of them included 5 events, 88 included 4 events, and 80 included 3 events.

- As a result of the quantitative FTA, the mean time of the system was found as 3.73 days. This means that a worker expectedly had an accident from roof and rib falls approximately every four days.

- Probability of failure of the system at 3.73 days was found as 59.39%. This means that system would fail with 60% probability at 4 days. Also, it was found that the probability of failure of the system became 100% at 20 days. This means, it was certain that a worker had an accident from roof and rib fall in 20 days.

- Then, independent probability of failure of each event at the mean time was evaluated. Events with the highest probability of failures were found as Insufficient Risk Assessment (0.9798), Lack of Additional Rock Supports (0.9710), Inadequate Job Training (0.9692), Poor Safety Culture (0.9637), and Insufficient Face and Roof Supports (0.9493). A comparison of the results of frequencies and probability of failures, revealed that first two events were parallel with the results found in qualitative section, however the alignment changed for the rest of the basic events.

- Insufficient risk assessment, which was examined under management error, had the highest probability of failure and frequency rate. The reason is due to the fact that this basic event had an effect on each of the accidents. An effective risk assessment is one of the most important issues in preventing accidents and fatalities in the research area. The risk assessment of the workplace was prepared poorly and did not contain all of the hazards and risks about roof and rib supports. Also, the specified hazards in that risk assessment generally had a conclusion of presence of lower risks in the workplace.

- In order to determine the effects of each event to the system failure, reliability of importance and static importance were evaluated. The most significant events by means of reliability importance were found as Improper PPE, Procedural Errors, Improper Tools, Failure to Take Control Measures, and Inexperience. The difference of these events from the events with the highest independent probability of failures were, these events directly affect the system failure, that if the preventive measures for these events were taken as the top priority, mean time for the system to be fail would increase.

- The event with the highest importance was Improper PPE with the importance value of 0.266. Improper PPE was evaluated under Management Error-Improper Equipment. Accidents related to head, feet, and eye was considered for this basic event.

- Procedural Errors had the second highest importance value of 0.244. Procedural errors were evaluated under Human Error. These were the errors, mistakes or violations of workers committed while applying the procedures.

- Third event with the highest importance was Improper Tools with 0.221. Improper tools were evaluated under Management Error and define the wrong or misused equipment in the research area such as improper scaling bars, improper drilling equipment.

- Then, it was assumed to prevent conditions that constitute Improper PPE, Procedural Errors, Improper Tools, Failure to Take Control Measures, and Inexperience, and fault tree reanalyzed accordingly. The results of this analysis showed that mean time of the system would increase to 6.74. This means that approximately every seven days, it is expected of a worker gets injured from roof and rib falls, if the first five events prevented, which is approximately twice of the first condition.

5.2 Recommendations

Main recommendations for future studies in this research domain are listed as the following:

- In the study improper PPE composed of improper foot, head and eye protectors. Head protectors in underground mining should stand for effects of minimum 10 – 15 kg of weighted material and should be used for maximum 3 years. Eye protectors are classified according to the tasks done. In underground coal mining glasses should be chosen according to the continuous use, steam proof and resistant to small pieces of rock. Foot protectors should also be chosen according to the job. For example, workers should wear anti-static shoes in environments which have explosion risks in order to conduct static electricity. In places that have a risk of electrical shock, insulated shoes should be preferred and none-slip boots should be preferred for muddy places. Roof and rib fall accidents of the feet are mainly contusions, twisting and fractures due to falling rocks. In that case foot protectors should be steel toed and impact resistant.

- Training programs in the research area are needed to be revised since some of the most significant events could only be prevented by efficient theoretical and practical trainings such as procedural errors, failure to control the preventive safety measures and workers' failure to take control measures.

- In order to prevent the accidents from improper tools, firstly proper scaling bars in accordance with the latest technological features should be provided. Secondly, light and ergonomic drilling equipment should be preferred in order not to cause any additional hazards.

- This risk assessment should be revised by a risk assessment team including, operation manager, OHS manager, occupational physician, employee representative, and other related staff. This thesis could be used as a reference for a risk assessment revision in the research area.

- In order to reduce the frequency of poor safety culture event, and increase the safety culture in the workplace, management should be aware of the hazards and current situation in the mine, and approach to safety as a significant issue. By changing the perception of safety, most of the accidents can be prevented. Safety culture is a unique subject itself, and it could be analyzed for further studies for this particular mine site.

- Mesh and screens can be used to prevent falls of smaller rocks. Meshes are generally used with rock bolts in underground applications to ensure the attachment of the mesh to the rock. Most accidents occurred in the study area are due to medium and small rock falls and one of the best ways to prevent these accidents is to use proper mesh with proper sizes. If the proper prevention methods for smaller rock and coal falls are taken, mechanized support system would be one of the best applications for the research area.

- Also, besides of the economic loss due to deferring the productions, there are insurance costs in the cases of accidents resulted in disability and fatality. This situation is not this study's scope, but it could be investigated in further studies. This study could be further developed in order to use in other underground coal mine for examining roof and rib fall accidents.

- In order to verify the results of this study, accident data from the beginning of 2014 could be gathered from the company and reanalyzed in order to see whether the roof and rib fall accidents occurred in exactly in maximum 20 days in the research area. This analysis could be made for the future studies.

- Also, this analysis could be applied to other underground hard coal mine sites of TTK, as well as other underground coal mines. Also, accident data gathered from the company could be organized in order to reduce the miscellaneous accidents, and by this way this analysis could be more precise and could be applied to all kinds of accidents and fatalities on the mine site.

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APPENDIX A

RESULTS OF RUNS TEST

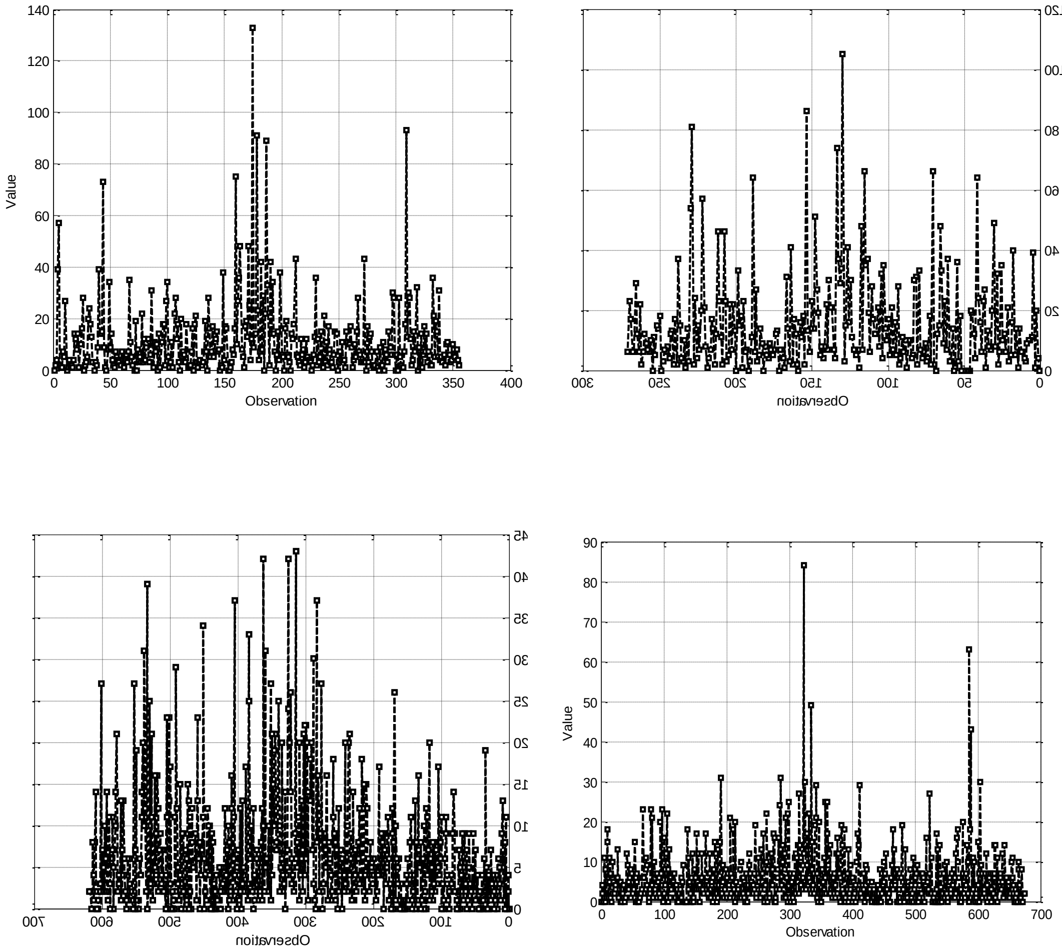

Figure A.1 Runs Test results for Events X1, X2, X3, XS

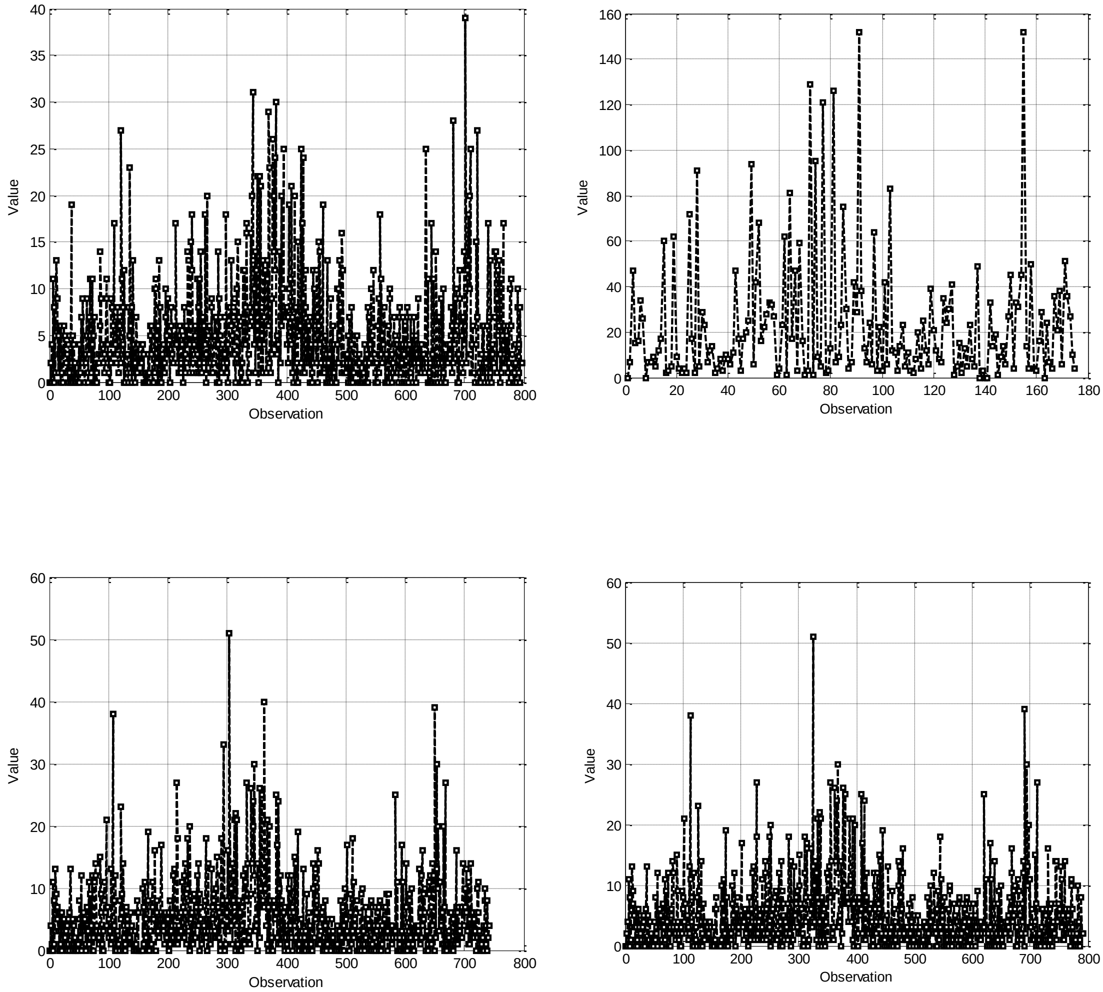

Figure A.2 Runs Test results for Events X7, X9, X10, XE

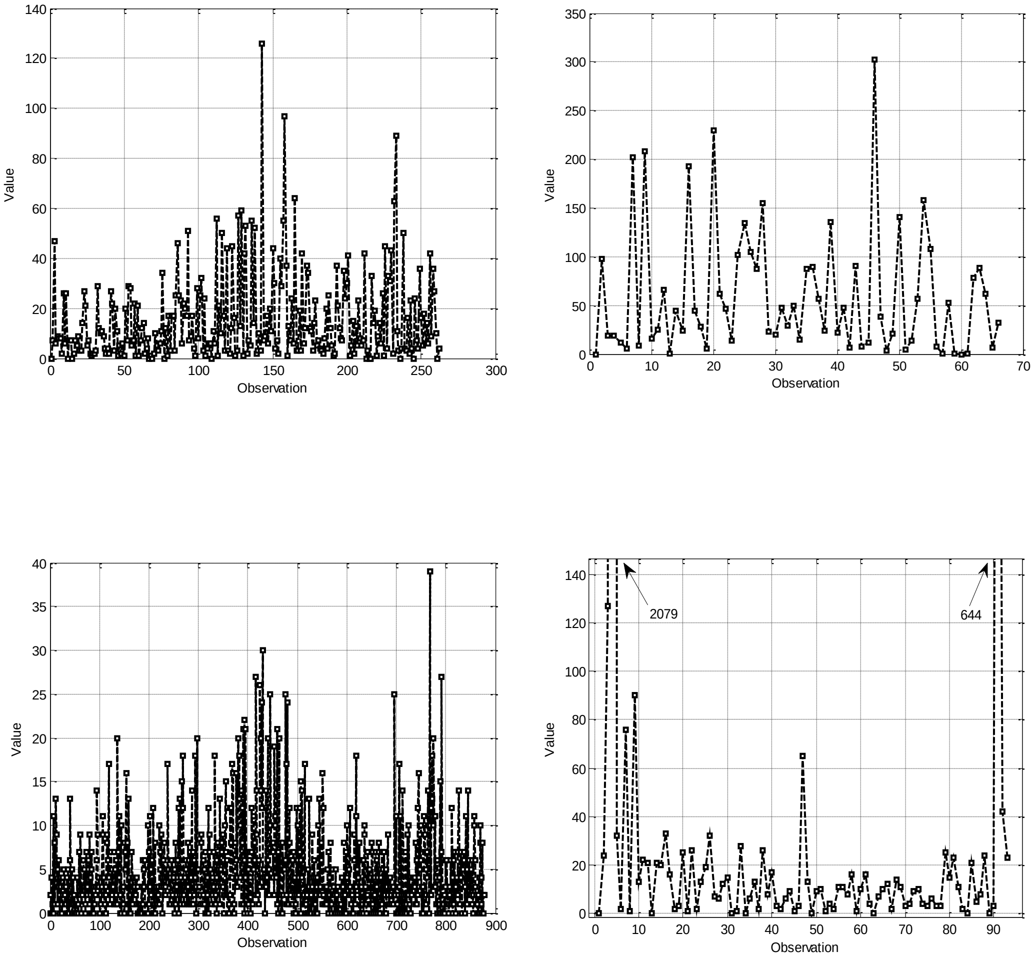

Figure A.3 Runs Test results for Events X16, X17, X18, X20

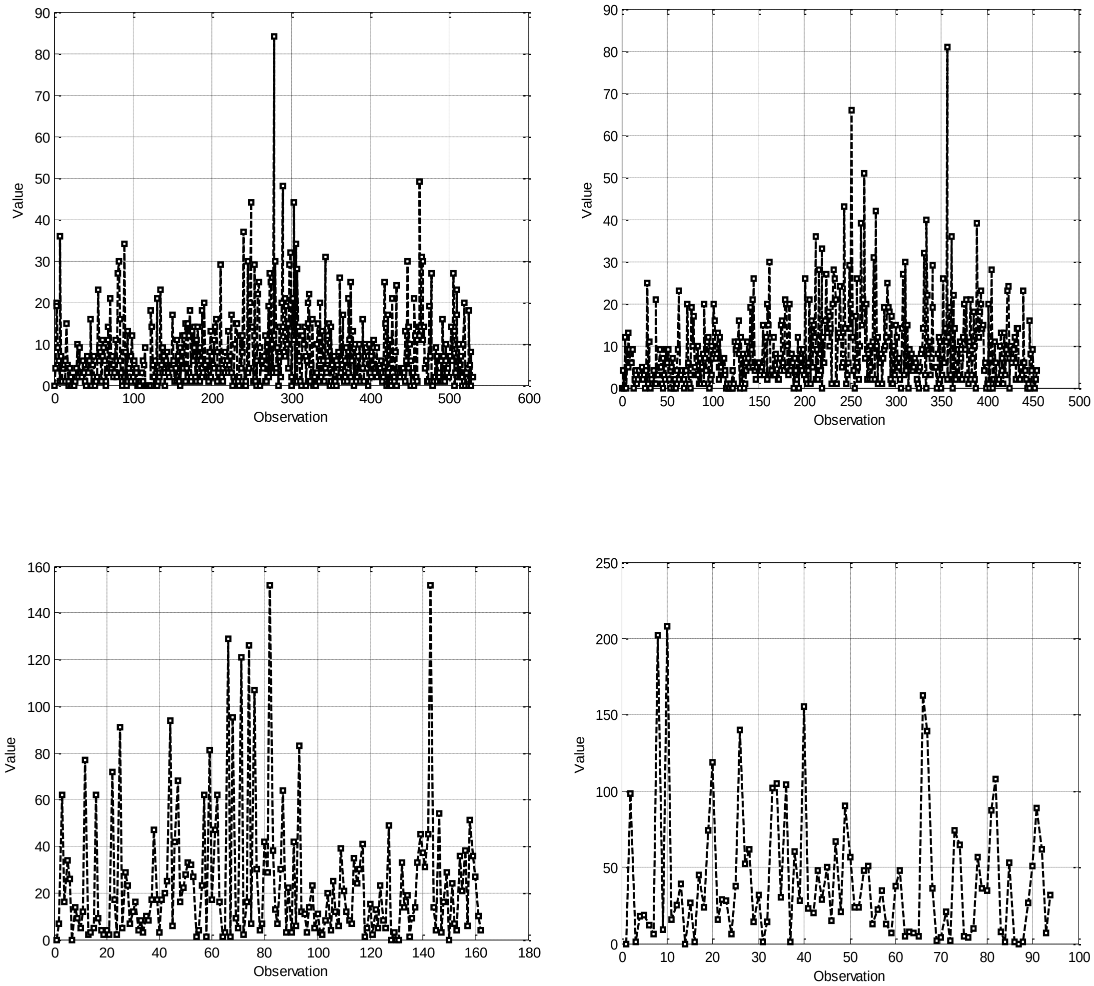

Figure A.4 Runs Test results for Events XP, X25, X26, X27

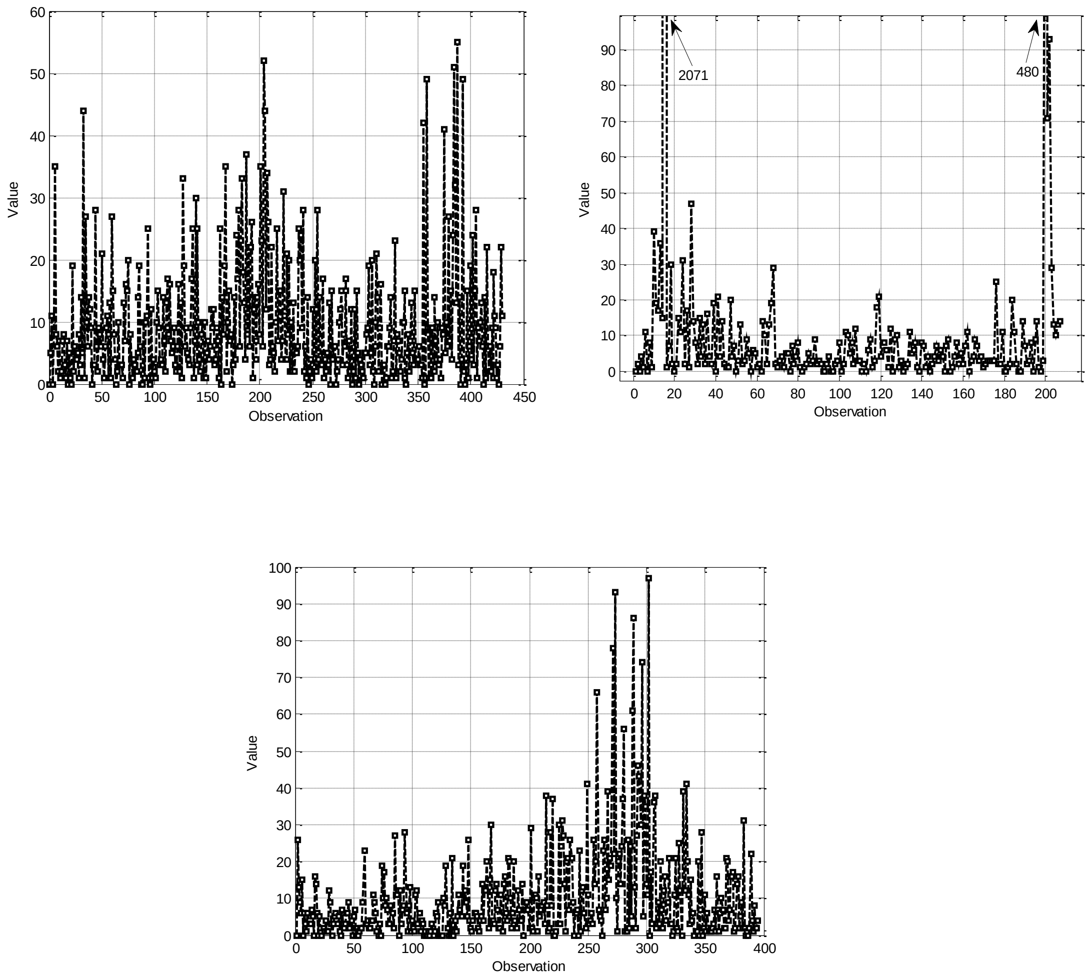

Figure A.5 Runs Test results for Events X35, X36, X38

APPENDIX B

MINIMAL CUT SETS OF FAULT TREE OF THE SYSTEM

Table B.1 Minimal Cut Sets

Set #	**Event width**	**Minimal Cut Sets**	**Set #**	**Event width**	**Minimal Cut Sets**
Set 1	3	X41, XP, X1	Set 159	4	X12, XE, X1, X21
Set 10	3	X28, X38, XS	Set 160	4	X39, X28, X23, X20
Set 11	3	X28, X38, X3	Set 161	4	X12, XE, X3, X23
Set 12	3	X9, X39, XP	Set 162	4	X12, XE, X2, X20
Set 13	3	X9, X39, X28	Set 163	4	XE, XS, X13, X20
Set 14	3	X29, X39, X1	Set 164	4	X29, X38, X21, X20
Set 15	3	X39, XP, XS	Set 165	4	X41, XP, X21, X20
Set 16	3	X19, X1, X23	Set 166	4	X30, X39, X23, X20
Set 17	3	X39, XP, X3	Set 167	4	X12, XE, X2, X23
Set 18	3	X39, X28, XS	Set 168	4	X41, X28, X21, X20
Set 19	3	X39, X28, X3	Set 81	4	X12, X9, XE, X21
Set 2	3	X29, X41, X2	Set 82	4	X19, XE, X3, X13
Set 20	3	X41, XP, X2	Set 83	4	XE, X1, X13, X21
Set 21	3	X9, X41, XP	Set 84	4	X19, X41, XP, X21
Set 22	3	X9, X41, X28	Set 85	4	X12, X19, XE, XS
Set 23	3	X3, X23, X20	Set 86	4	X19, XE, X2, X13
Set 24	3	X41, XP, XS	Set 87	4	XE, X2, X13, X20
Set 25	3	X9, X30, X38	Set 88	4	X19, X39, XP, X23
Set 26	3	X41, XP, X3	Set 89	4	X19, X28, X38, X21
Set 27	3	X41, X28, XS	Set 90	4	X12, X19, XE, X3
Set 28	3	X41, X28, X3	Set 91	4	X19, X41, XP, X23
Set 29	3	XP, X38, X1	Set 92	4	X19, X30, X41, X21
Set 3	3	XP, X38, X2	Set 93	4	X9, X19, XE, X13
Set 30	3	X28, X38, X1	Set 94	4	X30, X39, X21, X20
Set 31	3	X39, XP, X1	Set 95	4	X28, X38, X23, X20
Set 32	3	X39, X28, X1	Set 96	4	XE, X1, X13, X23
Set 33	3	X29, X38, X3	Set 97	4	X19, X39, X28, X23

Table B.1 Minimal Cut Sets (Continued)

Set 34	3	X9, X29, X39	Set 98	4	X19, X29, X41, X23
Set 35	3	X41, X28, X1	Set 99	4	XE, X2, X13, X21
Set 36	3	X29, X39, XS	Set 169	5	XE, X41, X28, X13, X21
Set 37	3	X28, X38, X2	Set 170	5	X19, XE, X28, X38, X13
Set 38	3	X30, X38, X1	Set 171	5	X12, X19, XE, X29, X39
Set 39	3	X9, X29, X41	Set 172	5	XE, X28, X38, X13, X21
Set 4	3	X9, XP, X38	Set 173	5	X12, XE, X29, X38, X21
Set 40	3	X30, X41, X1	Set 174	5	XE, X39, X28, X13, X23
Set 41	3	X29, X41, XS	Set 175	5	X12, XE, X28, X38, X23
Set 42	3	X39, X28, X2	Set 176	5	X19, XE, XP, X38, X13
Set 43	3	X9, X19, X21	Set 177	5	X19, XE, X29, X39, X13
Set 44	3	X19, X3, X23	Set 178	5	XE, X29, X39, X13, X21
Set 45	3	X19, XS, X21	Set 179	5	X12, XE, X41, X28, X23
Set 46	3	X19, X3, X21	Set 180	5	XE, X29, X41, X13, X21
Set 47	3	X9, X29, X38	Set 181	5	XE, XP, X38, X13, X23
Set 48	3	X2, X23, X20	Set 182	5	XE, X28, X38, X13, X23
Set 49	3	X29, X38, XS	Set 183	5	XE, X30, X41, X13, X21
Set 5	3	X9, X28, X38	Set 184	5	XE, X39, X28, X13, X21
Set 50	3	X19, X1, X21	Set 185	5	X12, X19, XE, X41, X28
Set 51	3	X2, X21, X20	Set 186	5	XE, X41, XP, X13, X21
Set 52	3	X30, X38, XS	Set 187	5	XE, XP, X38, X13, X21
Set 53	3	X30, X41, XS	Set 188	5	X12, XE, X30, X38, X21
Set 54	3	X41, X28, X2	Set 189	5	X12, XE, X30, X39, X21
Set 55	3	X29, X41, X1	Set 190	5	X12, XE, X30, X41, X21
Set 56	3	X29, X38, X2	Set 191	5	XE, X30, X38, X13, X23
Set 57	3	X19, X2, X23	Set 192	5	X12, XE, X29, X38, X23
Set 58	3	X29, X39, X2	Set 193	5	X12, XE, X39, XP, X23
Set 59	3	X9, X21, X20	Set 194	5	X19, XE, X41, X28, X13
Set 6	3	X39, XP, X2	Set 195	5	XE, X39, XP, X13, X21
Set 60	3	X19, XS, X23	Set 196	5	XE, X41, XP, X13, X23
Set 61	3	XS, X21, X20	Set 197	5	XE, X29, X38, X13, X23
Set 62	3	X3, X21, X20	Set 198	5	XE, X29, X39, X13, X23
Set 63	3	X29, X38, X1	Set 199	5	XE, X39, XP, X13, X23
Set 64	3	X30, X39, X1	Set 200	5	X19, XE, X30, X41, X13
Set 65	3	X30, X39, XS	Set 201	5	X12, X19, XE, X41, XP
Set 66	3	X30, X39, X3	Set 202	5	X12, XE, X39, X28, X23
Set 67	3	X9, X30, X41	Set 203	5	XE, X39, XP, X13, X20
Set 68	3	X29, X41, X3	Set 204	5	X19, XE, X29, X38, X13

Table B.1 Minimal Cut Sets (Continued)

Set 69	3	X1, X21, X20	Set 205	5	X12, XE, X30, X38, X23
Set 7	3	XP, X38, XS	Set 206	5	X12, XE, X30, X39, X23
Set 70	3	X29, X39, X3	Set 207	5	XE, X30, X38, X13, X21
Set 71	3	X9, X23, X20	Set 208	5	XE, X28, X38, X13, X20
Set 72	3	XS, X23, X20	Set 209	5	X19, XE, X39, XP, X13
Set 73	3	X19, X2, X21	Set 210	5	X19, XE, X41, XP, X13
Set 74	3	X30, X41, X2	Set 211	5	X19, XE, X29, X41, X13
Set 75	3	X9, X19, X23	Set 212	5	XE, X41, X28, X13, X20
Set 76	3	X1, X23, X20	Set 213	5	X12, X19, XE, X30, X38
Set 77	3	X9, X30, X39	Set 214	5	X12, X19, XE, X30, X39
Set 78	3	X30, X39, X2	Set 215	5	X12, XE, X30, X41, X23
Set 79	3	X30, X41, X3	Set 216	5	X12, XE, X29, X39, X21
Set 8	3	X30, X38, X2	Set 217	5	X12, XE, X29, X41, X21
Set 80	3	X30, X38, X3	Set 218	5	X12, X19, XE, X30, X41
Set 9	3	XP, X38, X3	Set 219	5	X12, XE, X29, X39, X23
Set 100	4	X9, XE, X13, X21	Set 220	5	X12, X19, XE, X29, X38
Set 101	4	XE, XS, X13, X21	Set 221	5	X12, XE, X28, X38, X21
Set 102	4	X12, XE, XS, X21	Set 222	5	X12, XE, X29, X41, X23
Set 103	4	X19, X29, X38, X21	Set 223	5	X12, XE, X39, XP, X21
Set 104	4	X12, XE, X2, X21	Set 224	5	XE, X29, X41, X13, X23
Set 105	4	XE, X2, X13, X23	Set 225	5	X12, X19, XE, X39, XP
Set 106	4	XE, XS, X13, X23	Set 226	5	X12, XE, X41, XP, X21
Set 107	4	XE, X3, X13, X23	Set 227	5	X12, XE, X41, X28, X21
Set 108	4	X39, XP, X23, X20	Set 228	5	XE, X30, X39, X13, X21
Set 109	4	X19, X39, X28, X21	Set 229	5	XE, X29, X38, X13, X21
Set 110	4	XE, X3, X13, X21	Set 230	5	XE, X41, X28, X13, X23
Set 111	4	X19, X29, X38, X23	Set 231	5	X12, X19, XE, X29, X41
Set 112	4	X19, X28, X38, X23	Set 232	5	XE, XP, X38, X13, X20
Set 113	4	X19, XE, XS, X13	Set 233	5	X12, XE, XP, X38, X20
Set 114	4	X12, X9, X19, XE	Set 234	5	X12, XE, X28, X38, X20
Set 115	4	X29, X38, X23, X20	Set 235	5	X12, XE, X39, XP, X20
Set 116	4	X29, X39, X23, X20	Set 236	5	X12, XE, X39, X28, X20
Set 117	4	X29, X41, X23, X20	Set 237	5	XE, X39, X28, X13, X20
Set 118	4	X19, X41, X28, X23	Set 238	5	X12, XE, X41, XP, X20
Set 119	4	X19, X30, X38, X23	Set 239	5	X12, XE, X41, X28, X20
Set 120	4	X19, X30, X39, X23	Set 240	5	X12, XE, X39, X28, X21
Set 121	4	X19, XP, X38, X21	Set 241	5	XE, X29, X38, X13, X20
Set 122	4	X12, XE, X1, X20	Set 242	5	XE, X30, X39, X13, X23

Table B.1 Minimal Cut Sets (Continued)

Set 123	4	XP, X38, X23, X20	Set 243	5	XE, X29, X39, X13, X20
Set 124	4	X28, X38, X21, X20	Set 244	5	XE, X41, XP, X13, X20
Set 125	4	X12, X9, XE, X23	Set 245	5	X19, XE, X30, X38, X13
Set 126	4	X12, XE, XS, X23	Set 246	5	XE, X29, X41, X13, X20
Set 127	4	X19, XP, X38, X23	Set 247	5	X19, XE, X30, X39, X13
Set 128	4	X12, XE, X1, X23	Set 248	5	XE, X30, X41, X13, X23
Set 129	4	X30, X41, X23, X20	Set 249	5	X12, XE, XP, X38, X23
Set 130	4	XE, X3, X13, X20	Set 250	5	X12, XE, X29, X38, X20
Set 131	4	XP, X38, X21, X20	Set 251	5	X12, XE, X29, X39, X20
Set 132	4	X12, X9, XE, X20	Set 252	5	X12, XE, X29, X41, X20
Set 133	4	X19, XE, X1, X13	Set 253	5	X12, XE, XP, X38, X21
Set 134	4	X12, X19, XE, X1	Set 254	5	XE, X30, X38, X13, X20
Set 135	4	X19, X41, X28, X21	Set 255	5	X12, X19, XE, XP, X38
Set 136	4	X39, X28, X21, X20	Set 256	5	XE, X30, X39, X13, X20
Set 137	4	X9, XE, X13, X23	Set 257	5	X12, X19, XE, X28, X38
Set 138	4	X19, X30, X41, X23	Set 258	5	XE, X30, X41, X13, X20
Set 139	4	X19, X29, X39, X21	Set 259	5	X12, X19, XE, X39, X28
Set 140	4	X19, X30, X39, X21	Set 260	5	X19, XE, X39, X28, X13
Set 141	4	X30, X41, X21, X20	Set 261	5	X12, XE, X41, XP, X23
Set 142	4	X9, XE, X13, X20	Set 262	5	X12, XE, X30, X38, X20
Set 143	4	X12, X19, XE, X2	Set 263	5	X12, XE, X30, X39, X20
Set 144	4	X19, X29, X41, X21	Set 264	5	X12, XE, X30, X41, X20
Set 145	4	X19, X30, X38, X21	Set 152	4	X30, X38, X23, X20
Set 146	4	X29, X41, X21, X20	Set 153	4	X12, XE, X3, X21
Set 147	4	X19, X29, X39, X23	Set 154	4	X41, X28, X23, X20
Set 148	4	X39, XP, X21, X20	Set 155	4	X30, X38, X21, X20
Set 149	4	X12, XE, XS, X20	Set 156	4	X29, X39, X21, X20
Set 150	4	XE, X1, X13, X20	Set 157	4	X41, XP, X23, X20
Set 151	4	X12, XE, X3, X20	Set 158	4	X19, X39, XP, X21