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Risk Management for Surface Plants in Mines using Risk Matrix and BowTie Analysis

***Muharrem Kemal OZFIRAT*[1]*, *Pinar Mizrak OZFIRAT*[2] and *Mustafa Emre YETKIN*[3]**

Authors' affiliations and addresses:
[1] Dokuz Eylul University, Mining Engineering Department, 35160 Buca-Izmir/Türkiye
e-mail: kemal.ozfirat@deu.edu.tr

[2] Manisa Celal Bayar University, Industrial Engineering Department, Manisa/Türkiye
e-mail: pinar.ozfirat@cbu.edu.tr

[3] Dokuz Eylul University, Mining Engineering Department, 35160 Buca-Izmir/Türkiye
e-mail: mustafa.yetkin@deu.edu.tr

***Correspondence:**
Muharrem Kemal Ozfirat, Dokuz Eylul University, Mining Engineering Department, 35160 Buca-Izmir/Türkiye
tel.:+90 232 301 75 39
e-mail: kemal.ozfirat@deu.edu.tr

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Abstract

Surface plants in mines are important parts of a mine operation. There exist offices, common areas, repair and maintenance shops, compressed air facilities, hydraulic facilities, areas where mine machinery and parts are stacked, transportation cranes and mine stock areas in surface plants. Therefore, while the mining operations are continuing, it is necessary to control all the work in the surface plants in terms of work safety and health. In this study, the risk matrix method is used to identify and prioritize the risks of surface plants in a mine. Then, the highest priority risk, which is found to be "Stock area and work environment", is considered using bowtie analysis. Four threats are determined for "Stock area and work environment" risk. These are improper ore or coal stock area, insufficient lighting in night works, lack of maintenance of field crane and dusty work environment. These threats are also modelled using bowtie analysis. As a result of this study, these threats, corresponding barriers and consequences can be managed by safety and operational engineers.

Keywords

Mine surface plants, Risk matrix, BowTie analysis, BowTieXP software.

Introduction

The mining industry is one of the high-risk working areas. Therefore risk analysis and control is an important subject in this area. Recently, Ismail et al. (2021a) have presented a literature survey on the studies considering the causes and prevention of mining accidents as well as actions to be taken and the effects of mining accidents. In addition, the authors have also identified the effective factors presented in the literature for mining safety (Ismail et al. 2021b).

One of the facilities which exist both in open pit and underground mines is the surface plant. Surface plants in mines contain the required utilities for operations in mines. These utilities include sections such as ventilation, maintenance works, transport facilities, stock areas, explosive storage, management buildings and dressing rooms (in underground mines). In the mine operation, when the ore is produced from the mine, it is transported to process. The surface facilities should not be installed within ore boundaries, transportation and influence areas. Otherwise, as the mine operation area gets wider, transportation of ore would get much harder and risky. Therefore, surface plants in the mines should be established considering production rates and zones. The location and order of settlement of surface plants are different according to the mining operation method and condition of stocked ore.

In this study, hazards that may occur in surface plants are identified, and suggestions are given on work safety precautions. Firstly, the risk matrix method is used to define risks in surface plants. Using the result of risk matrix analysis, the highest priority risk is identified. Then, bowtie analysis is carried out to take the risk under control using proactive and reactive preventions.

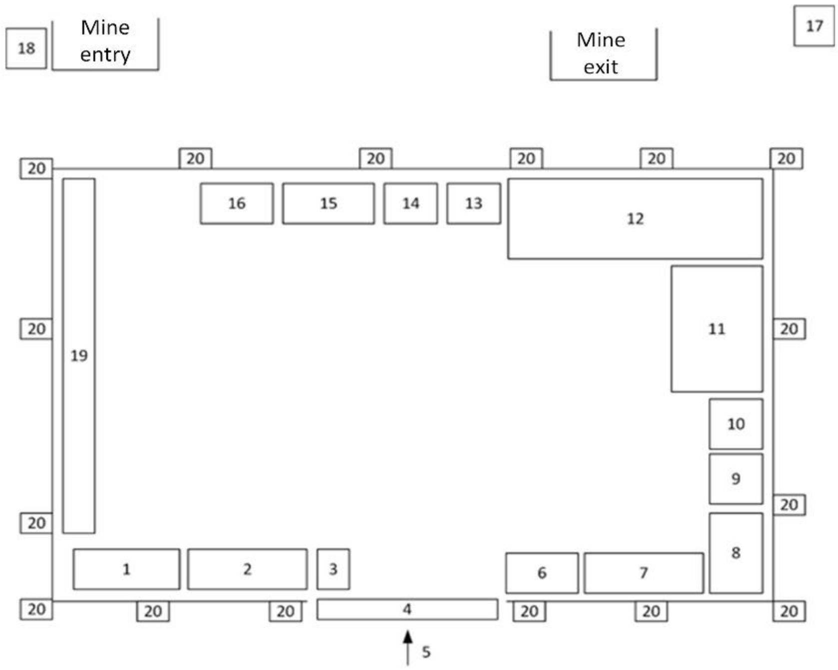
Risk matrix and bowtie analysis are well-known risk analysis methods, especially for the mining industry. The risk matrix method is often used to do preliminary hazard analysis. Pamukcu (2015) employs this method to identify moderate and higher risks for tunnel construction projects and further analyses the risks using event tree analysis. Dominguez et al. (2019) also apply the risk matrix method for underground mining. Korshunov et al. (2020) handle the risk matrix method, further develop it to overcome some disadvantages and apply it to a mining company. A recent study (Hao and Nie, 2022) also proposes a hierarchical risk analysis model made up of multi-layers and integrates this model into the risk matrix method. The authors use this method for risk evaluation in the mining industry.

On the other hand, bowtie analysis is also a preferred method for the mining industry. Sharafat et al. (2021) propose a new risk analysis methodology integrating bowtie analysis with event tree and fault tree analysis methods. The authors present an application of the methodology for a tunnel-boring machine case. Thienen-Visser et al. (2014) handle gas oil leakage and present risk analysis based on bowtie. In Xie et al. (2021), a bowtie analysis is carried out for an oil depot fire and explosion event. Then, a quantitative risk evaluation methodology is defined based on the risk matrix and cloud theory.

Within the scope of this study, preliminary hazard analysis for surface plants of mines is carried out using the risk matrix method. The risks identified are further analyzed using bowtie analysis. Causes and consequences of events as well as proactive measures (to prevent causes) and reactive measures (to protect from consequences), are presented.

Surface Plants in Mines

When establishing the surface plants in a mine, the ground state, whether the ground is capable of carrying the structure, topographical and geological conditions of the area, and surface and underground water conditions should be examined. After these studies, installations are established, and a location plan is drawn. An example surface location plan for a mine is given in Figure 1. The stock area, ore preparation facilities, explosive material storage, management buildings, lamb cabin, dormitory, maintenance-repair workshop, hydraulic-pneumatic facilities and dining hall buildings need to be shown on the plan for an underground mine. Soil should be classified as which is used for buildings. Difficult weather conditions (such as wind, wind load and snow conditions) should be considered because mining operations are generally in difficult regions. For efficient and strong buildings, heat insulation should be considered. The construction of electrical lines and insulations is also an important issue.



1:maintenance-repair building and crane 2:engineer and manager rooms, underground monitoring system rooms 3:main entrance 4:entrance door 5:entrance 6:dining hall 7:dormitory, bathroom and toilets 8:lamp cabin 9:support store 10:hydraulic-pneumatic 11: ore stock area 12:mineral processing plant and silo 13:generator 14:wood processing 15:work safety unit 16:auxiliary material storage 17:explosive storage 18:main and standby fan 19:maintenance-repair building service road (from underground) 20: lighting columns

Fig. 1. Sample surface plants view for a mine

Defining Risk Sources in Surface Plants

In order to provide safe and efficient work in the mine, it is necessary to make risk management regularly for the surface plants. Some of the important hazard sources that may occur during the processes in surface plants are dust, electricity, noise and vibration, natural events, working at a high level, explosives and stock areas.

Dust is an important hazard source since it may cause occupational diseases and explosions in enclosed areas. According to the Turkish dust control regulation (2013), dust is defined as a particle that has the potential to spread to the work environment atmosphere. In particular, coal and metal dust are explosive, and sources of occupational illnesses. For this reason, it is important that the crushers and belt conveyors, which are frequently used in mine surface plants, should be operated in closed mode. In addition, employees should use dust-prevention equipment.

Another risk source is electricity. In electricity usage, the important issues are cables and their insulations. In addition, leakage relay, grounding line and lightning rod are very important in surface plants. Also, all measurements should be taken against short-cuts and fires (Birecikli, 2010).

The other risk sources are noise and vibration. Mines may face noise and vibration from surface operations. According to Turkish noise regulation (2013), control measures should be taken when noise exceeds 80 dB(A). In addition, vibration may occur due to the operation of machinery and equipment. In Turkish vibration regulations (2013), vibration is split into two parts as hand-arm vibration and whole-body vibration. Daily exposure limits are defined for both vibration types.

Natural events are also important in mines. Most of the mines are located in rural areas or mountain regions. Therefore, natural events are highly probable. It is necessary to protect the surface plants of a mine against natural events such as strong storms, rain, snow and lightning. In order to do so, plants should have strong buildings, and emergency situation plans should be made. Vanek et al. (2020) consider natural events as environmental risks and handle these events using Failure Modes and Effects Analysis (FMEA).

In addition, some operations are performed at high levels. Corrective measures are very important in this case as well as personal protection measures such as parachute-type safety belts, anchors, etc.

Explosive materials and their storage are important issues for production in mines. There are many rules and regulations about keeping explosive materials. These rules should be taken into consideration in detail. For example, explosive materials should be kept in a safe place, and unauthorized people should not be allowed inside.

Storage area of the ore/coal is also important in a mine. Storage geometry should be considered according to the properties of the ore/coal. In addition, there may be other risks, such as fire and/or oxidation in the storage area. For instance, coal storage may lead to spontaneous combustion fire in case of inaccurate storage (Demirel et al., 2013; Unver and Ozozen, 1998).

Proposed Risk Analysis Methodology

Risk analysis starts with defining the possible hazards. Hazard is defined by World Health Organization (WHO) as an object, circumstance or factor that involves unfavorable effects on human health and environmental conditions. Risk, on the other hand, is defined by WHO as an undesirable result of an event depending on probability. In addition, International Labor Organization (ILO) defines risk as the probability of occurrence of an undesirable event under particular conditions or at a particular time.

Risk evaluation is the process of identifying sources, defining risk factors, computing and prioritizing risks and finally, determining measures to reduce risks (Ozfirat et al. 2019). In OHSAS 45001 Work Health and Safety Management System, risk evaluation is defined as the process of forecasting risk priority and resolving tolerable and intolerable risks (Ozkilic, 2014). For intolerable risks, prevention measures should be taken in order to put hazard sources away. Another way to deal with intolerable risks is to decrease the probability or severity of the risk using necessary precautions. In addition, risk management should be a continuous process similar to the risk management algorithm provided by Tworek et al. (2018). Once the risks are reduced, the process should continue by monitoring and going back to the risk evaluation step if necessary.

The main principle in work health and safety is the Plan–Do–Check–Act Cycle (PDCA). PDCA cycle is used to figure out the reasons for change and improve quality (Figure 2).

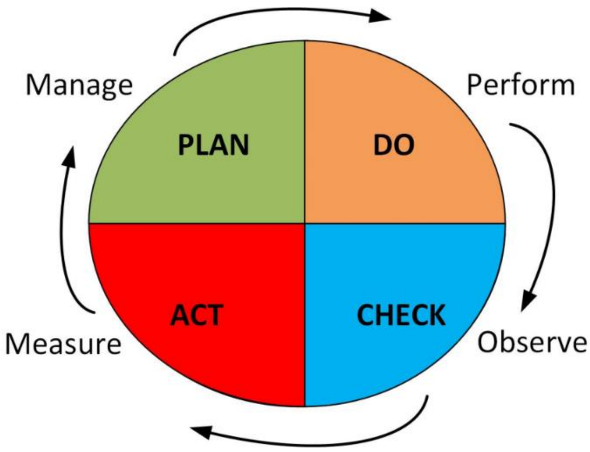


Fig. 2. PDCA Cycle (Ozkilic, 2014; Ozfirat et al., 2019)

The Plan–Do–Check–Act Cycle steps can be given as (Ozkilic, 2014; Ozfirat et al., 2019).

Plan: Find out the case where corrections are necessary. Then plan the necessary change for the recovery.

Do: Control the plan by trying it on a small case study.

Check: Check the results of the small case study.

Act: According to the output of the "Check" step, there are two actions:

- If the plan gives desired results for the case study, execute it for the real case. Go to the "Plan" step.
- If the plan does not give desired results, update the plan. Go to the "Plan" step.

There are a variety of risk analysis techniques which is based on the main Plan–Do–Check–Act cycle. Some of the widely used hazard identification techniques are listed in Tripathy and Ala (2018). In this study, risk matrix and bowtie analysis are integrated as the output of the risk matrix method becomes the input of bowtie analysis.

Risk Matrix Method

In this study, firstly, the risk matrix method is used to identify possible risks in the surface plants of a mine. Risk scores are computed for these risks. Then the highest priority risk is found, and bowtie analysis is performed for this risk. In this way, possible causes and probable effects are trying to be decreased.

In the risk matrix method, risk scores are obtained by multiplying risk severity and probability (Equation 1).

$$\text{Risk Score} = \text{Probability} \times \text{Severity} \quad (1)$$

Probability values are determined over a scale of five points according to their occurrence frequency. Similarly, severity values are also determined over a scale of five according to the effect of the results. Table 1 below displays probability and severity scales. In addition, possible risk scores can also be seen in Table 1.

Tab. 1. Risk score and classification (Ozkilic, 2014; Ozfirat et al., 2017)

Probability	Description of probability	1 time every x. years	Severity				
			(1) Negligible	(2) Marginal	(3) Critical	(4) Serious	(5) Catastrophic
(1) Very rare	Virtually impossible	>20	1	2	3	4	5
(2) Rare	Unlikely	3-20	2	4	6	8	10
(3) Occasional	May happen a few times, at least once	1-3	3	6	9	12	15
(4) Probable	May happen several times	Once every 6 months	4	8	12	16	20
(5) Frequent	May happen often	>Once every 6 months	5	10	15	20	25

After finding the risk scores, results are categorized, and possible actions are defined in the risk matrix method. Table 2 displays the possible results and preventive actions.

Tab. 2. Risk score and management (Ozkilic, 2014; Ozfirat et al., 2017)

Result	Preventive action
Intolerable risks (25)	Work should not be started until the risk is reduced. Any ongoing activity must be immediately stopped. If the risk is not reduced, the activity must be immediately stopped.
Important risks (15–20)	Work should not be started until the risk is reduced. Any ongoing activity must be immediately stopped. After preventive measures are applied, work can be continued.
Moderate-level risks (8–12)	Risk mitigation measures should be applied. Work can be continued.
Tolerable risks (2–6)	The risk is low, and further risk-reducing measures are not required. However, existing controls should be continued.
Insignificant risk (1)	Existing controls should be continued.

In the proposed approach, important and intolerable risks, where the risk score exceeds 15 according to Table 2, are determined to be considered by bowtie analysis to decrease risk level.

BowTie Analysis

Risk in bowtie methodology is based on the investigation of relations between hazards, top event, threats and consequences. Barriers are used to show the measures taken by an organization to control the risk. The left side of the bowtie displays proactive precautions which try to eliminate reasons for accidents. These are valuable barriers in trying to avoid accidents based on the "control at the source" principle. On the other hand, the right side of the bowtie displays the results of the accidents. Reactive precautions are planned in order to reduce the effect of these results, which mainly depend on the "control in the environment and person" strategy. The general bowtie diagram can be seen in Figure 3 below.

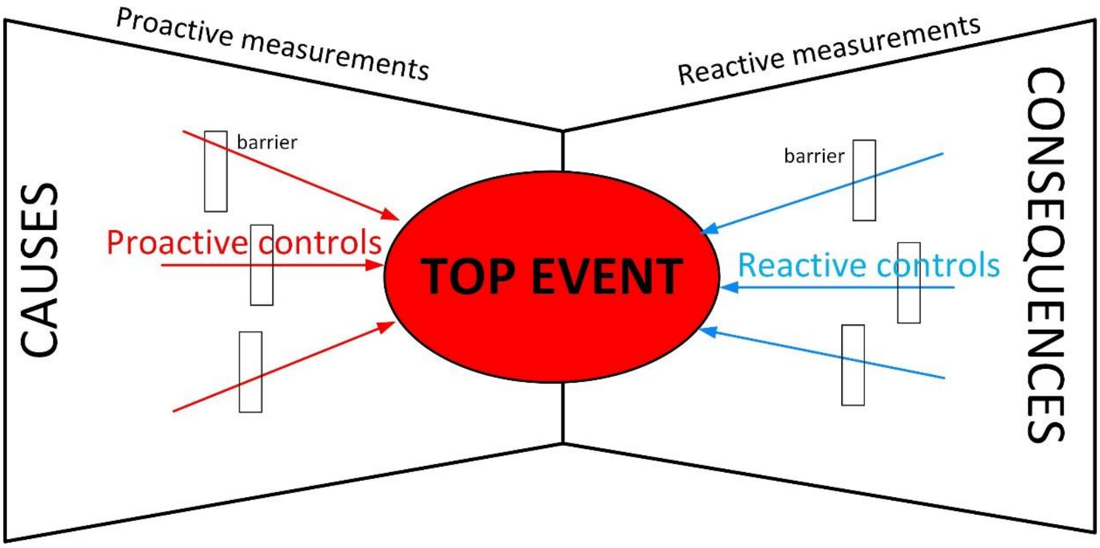


Fig. 3. General Bow Tie Schema

As seen in Figure 3, bowtie analysis is an advantageous method to understand the causes and results of potential risk. In addition, suggested precautions are classified as proactive and reactive measures. In this way, it would be easier to analyze and reveal the effect of these measures on the probability and severity of the top event separately. One of the drawbacks stated in the literature for bowtie analysis is that it does not present a quantitative analysis. However, in this study, BowTieXP (2020) software is employed, which also integrates a risk matrix evaluation based on a 6x5 matrix (Table 3) scale.

In Table 3, the scale for probability is given with letters "A, B, C, D and E", where "A" represents minimum probability and "E" represents maximum probability. The definitions are also given in Table 3. The reader should note that according to these definitions, it is easier to determine the probability of an event. Furthermore, the severity scale is made up of six levels from 0 to 6. Similar to probability, using this scale makes it easier to determine an event's severity value. In the table, green cells represent insignificant risk levels, yellow represents tolerable risk levels, orange represents moderate risk levels, and red represents important and intolerable risk levels. With the case handled in this study, evaluations according to Table 3 are also included in the bowtie analysis.

Tab. 3. "6x5 "risk matrix incorporated in BowTieXP (2020) software.

	A	**B**	**C**	**D**	**E**
0 No injury	A0	B0	C0	D0	E0
1 Slight injury	A1	B1	C1	D1	E1
2 Minor injury	A2	B2	C2	D2	E2
3 Major injury	A3	B3	C3	D3	E3
4 Single fatality	A4	B4	C4	D4	E4
5 Multiple fatalities	A5	B5	C5	D5	E5
A: Never heard of an incident in the industry B: An incident has occurred in the industry C: An incident has occurred in the company D: Happens several times per year in the company E: Happens several times per year in the location					

Case Study

In this study, possible risks are defined for surface plants of mines. These are dust, electricity, noise and vibration, natural events, working in high levels, explosives and stock area-work environment, respectively. Probability values, severity values and risk scores according to the risk matrix method can be seen in Table 4 below.

Tab. 4. Risk matrix analysis for surface plants of mines

Risk	Hazard Definition	Effects	Risk mitigation measures	P	S	RS
R1	Dust	Occupational illness	Dust should be suppressed and removed from the working area.	3	3	9
R2	Electricity	Injury and fatal accident	Insulation of the main electrical distribution panel, periodic maintenance and control.	3	4	12
R3	Noise and vibration	Occupational illness	Noisy machine and equipment should be controlled at their sources.	3	3	9
R4	Natural events	Injury and fatal accident	The bounding channel should be made all around the mine in order to prevent water flood. The lightning rod should be installed for lightning at determined places.	2	5	10
R5	Working in high level	Injury and fatal accident	Workers should be informed before working at a high level and use steel rope and safety belts for walking on scaffolding.	2	5	10
R6	Explosives	Injury and fatal accident	Explosive storage should be ventilated temperature as between 8-30 degrees. There must be a copper plate at the entrance for discharging static electricity.	2	5	10
R7	Stock area and work environment	Injury	Stock area and work environment should be done properly, and air contact should not be allowed to ore and coal.	4	4	16

P=Probability, S=Severity, RS=Risk Score

As seen in Table 4, the experts and authors give the severity value 5 for R4, R5, and R6 risks. The severity values of R2 and R7 are determined to be 4. In addition, the highest probability occurs for accidents caused in the stock area and work environment. Therefore, the probability value for R7 is determined to be 4. The risk score for R7 is computed to be 16. R7 has the highest priority, and it is determined to be in the high-risk group (Important risk, according to Table 2). Therefore work operations should not start until the risk score is decreased for R7. Other risks, which are electricity, dust, natural events, working at high levels, explosives, noise and vibration, should be followed to keep at acceptable risk levels.

In the second step of the study, in order to decrease the risk level of R7 (Stock area and work environment), bowtie analysis is performed. The bowtie diagram can be seen in Figure 4.

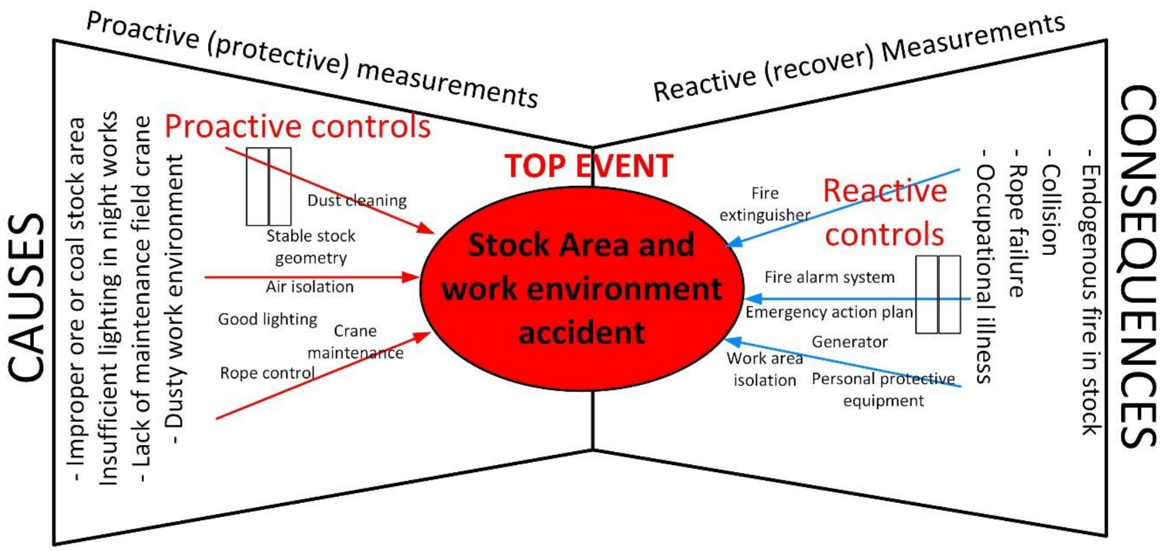


Fig. 4. Bowtie analysis for "Stock area and work environment" top event.

As seen in Figure 4, four threats are determined for the "Stock area and work environment" risk. These are improper ore or coal stock area, insufficient lighting in night works, lack of maintenance of field crane and dusty work environment. The top event, which is "Stock area and work environment", the four threats identified for the top event, corresponding barriers and the consequences can be seen in Figure 5 bowtie analysis. All analysis is carried out using BowTieXP software (2020). In Figure 5, proactive barriers to threats can be seen on the left side of the bowtie, whereas reactive barriers and the consequences can be seen on the right side of the bowtie. The main hazard on the top event is the coal (or ore) kept in the stock area. In this figure, it can be noticed that threats, barriers and consequences are presented in blue, white and red boxes, respectively.

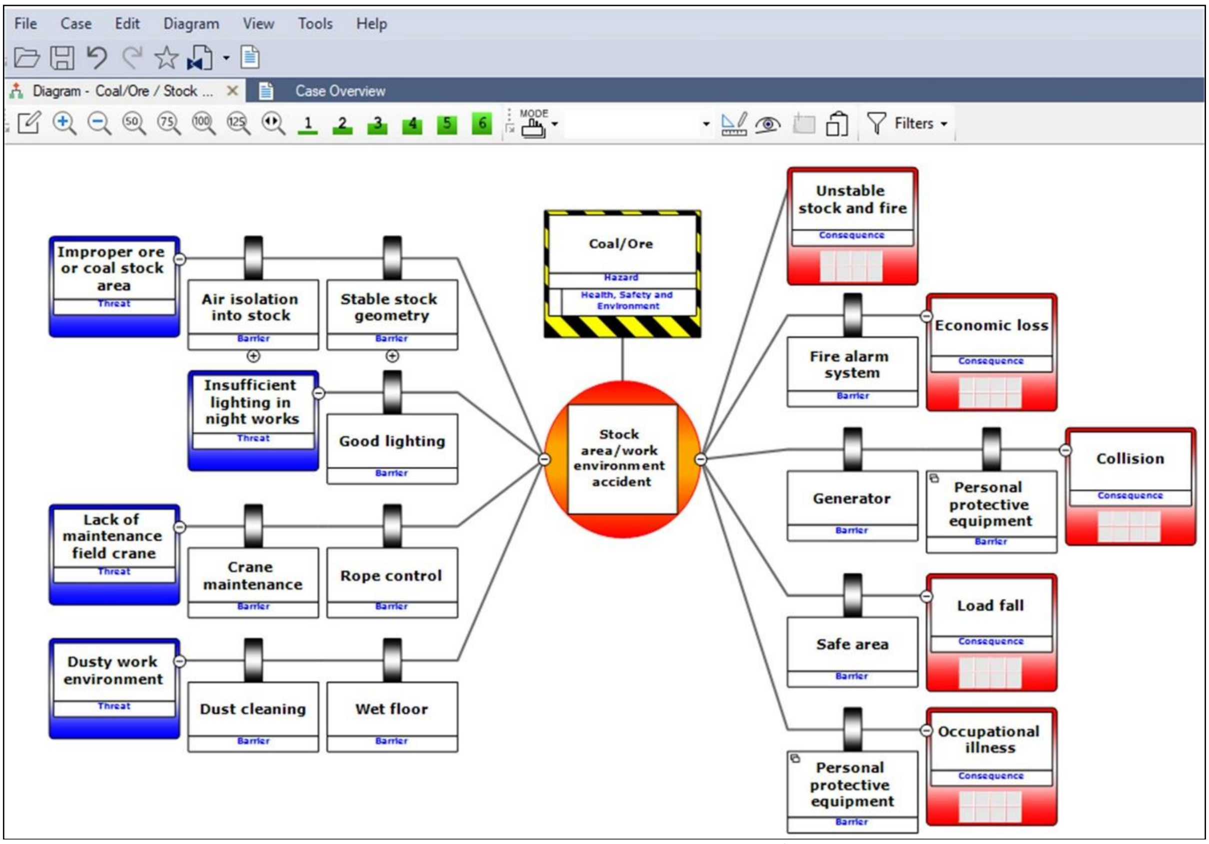


Fig. 5. Bow tie analysis in Bow Tie XP Software.

Each of the four threats identified in Figure 5 is also considered in detail using BowTie analysis (2020).

Threat 1- Improper ore or coal stock area: The bowtie diagram for the "Improper ore or coal stock area" threat is developed by BowTieXP (2020) and can be seen in Figure 6. The barriers to this threat are determined to be "air isolation into stock" and "stable stock geometry". As can be seen in Figure 6, these two barriers are proactive barriers, and they are given on the left side of the bowtie. In addition, escalation factors are also identified in the diagram (presented in yellow boxes), which are the factors that may decrease the effectiveness of the barrier. The escalation factor on the "air isolation into stock" barrier is isolation material failure. The escalation factors on "stable stock geometry" are weather conditions and stock design failure. On the right side of the bowtie (Figure 6), the consequences of the "Improper ore or coal stock area" threat are given. These are "unstable stock and fire" and economic loss. The reactive barriers to these consequences are fire alarm systems and insurance, respectively.

In elements of the bowtie diagram developed by BowTieXP (2020) software, some technical properties are also presented. These technical constraints are frequency of threats (for example, Frequency of "Improper ore or coal stock area" is 6 months.), degree of contribution, the importance of barriers (for example, Degree of contribution of "air isolation into stock" is very good and importance is highly critical) and risk assessment of consequences on worker, asset, environment, prestige perspectives. Risk assessment is performed both for inherent and residual risks based on the scale given in Table 3. For example, looking at the risk matrix given for "unstable stock and fire", it can be seen that inherent risk for worker, asset, environment and prestige are determined to be "D4, C4", "D4", and "C4", respectively. On the other hand, residual risk for worker, asset, environment and prestige are determined to be "C4, B4, C4", and "B4", respectively (Figure 6).

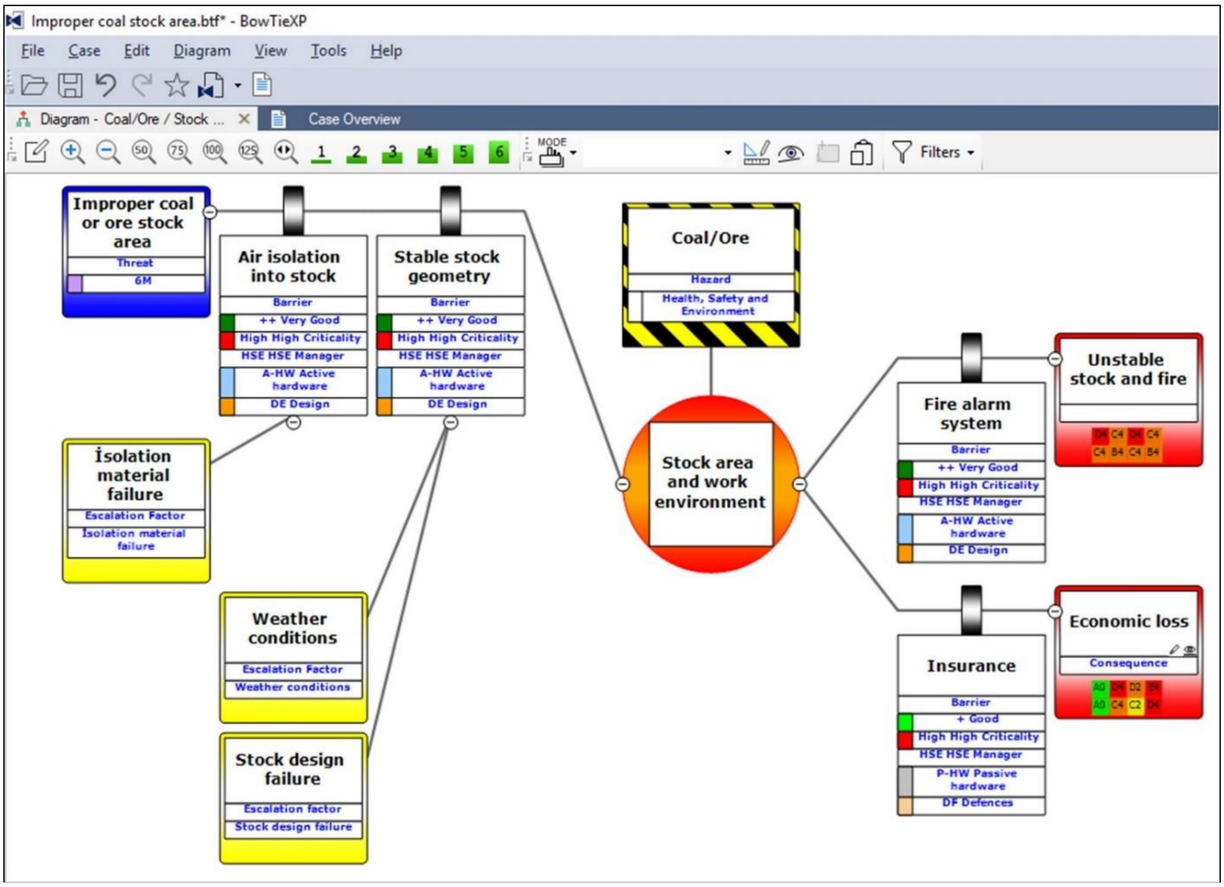


Fig. 6. Improper coal or ore stock area modelling in BowTieXP Software.

Threat 2- Insufficient Lighting in Night Works: The bowtie diagram for the "Insufficient Lighting in Night Works" threat is developed by BowTieXP (2020) and can be seen in Figure 7 below. The proactive barrier is determined to be good lighting. On the right side of the bowtie, the consequence of "Insufficient Lighting in Night Works" is a collision, and the reactive barriers are suitable rest time for the vehicle operator, reflector sign on the vehicle and vehicle horn system.

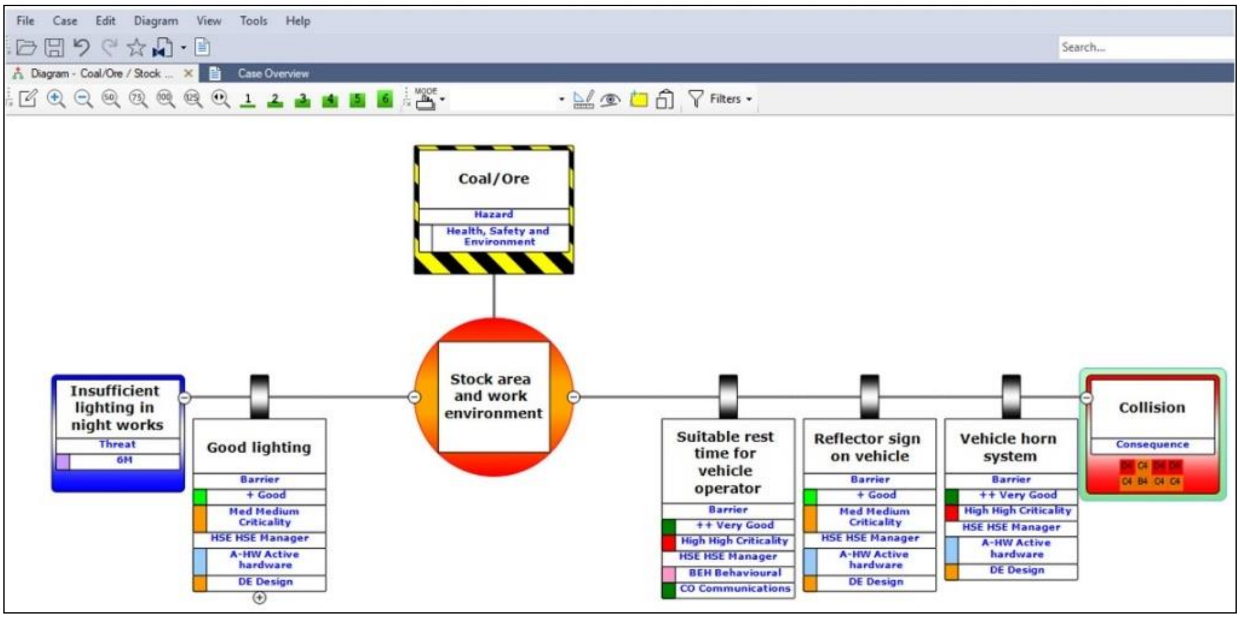


Fig. 7. Insufficient lighting modelling in BowTieXP Software.

Threat 3- Lack of maintenance of field crane: Similar to previous threats, the bowtie diagram for the "Lack of maintenance of field crane" threat is also developed by BowTieXP (2020) and is given in Figure 8. The field crane should be periodically checked every six months. Proactive barriers are determined to be crane maintenance and rope control. Since the rope is exposed to bending tension, it is especially important, and its maintenance should be periodically made. The consequence of this threat may be load fall. Therefore, the reactive barriers are determined to provide an entrance forbidden area for the crane (only the crane operator is permitted) and a safe area for the crane operator. In the case of these two barriers, even if a load fall occurs, it would have a small/no effect since there will be no workers in the area.

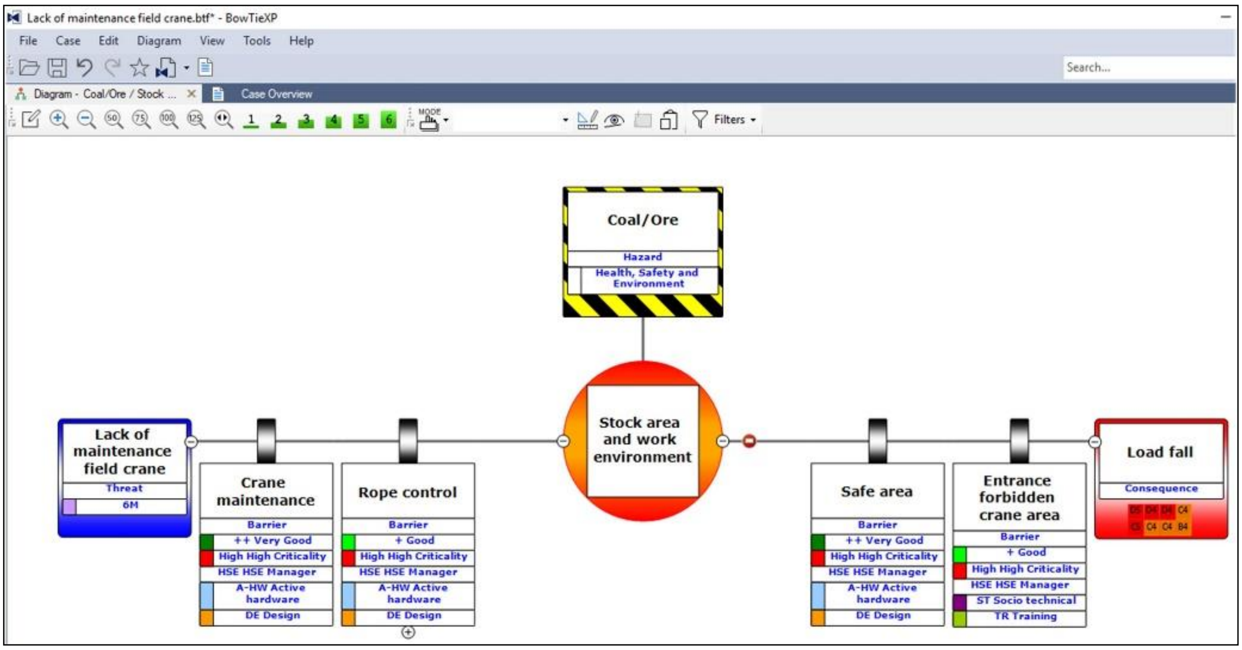


Fig. 8. Lack of maintenance field crane modelling in BowTieXP Software.

Threat 4- Dusty work environment: Bowtie diagram for the "Dusty work environment" threat which is developed by BowTieXP (2020), can be seen in Figure 9. Dust is a very hazardous factor in terms of occupational illnesses, especially in closed areas. Therefore, proactive barriers are determined to be dust cleaning as well as keeping the floor wet, and a reactive barrier is determined to be the use of personal protective equipment. Dust cleaning should be done weekly and should be completely removed from the work environment.

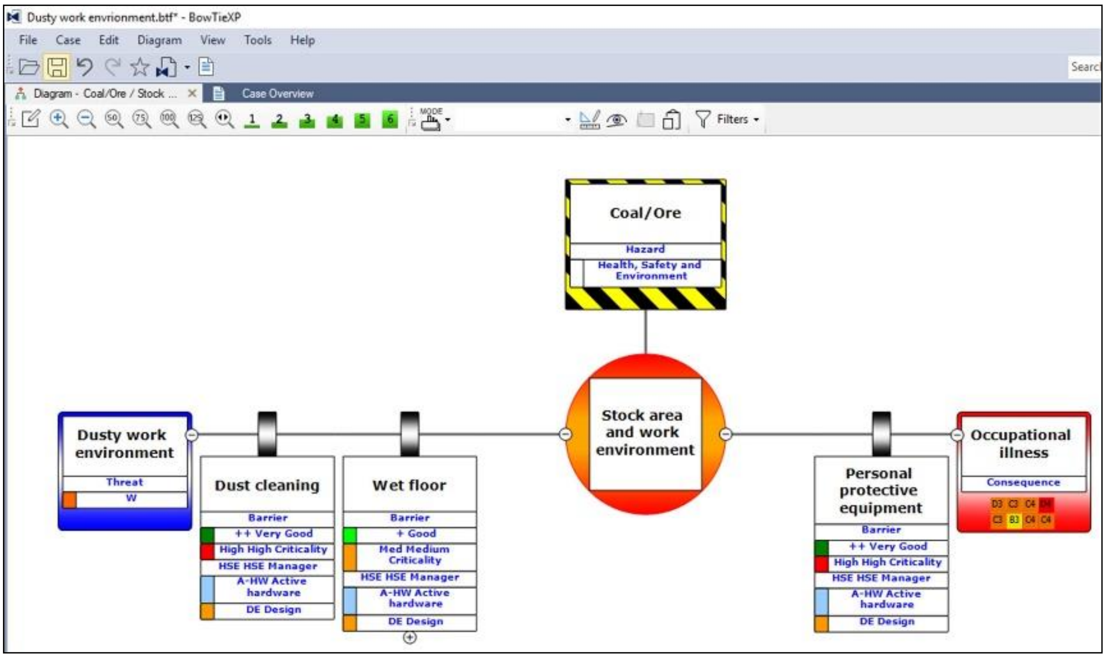


Fig. 9. Dusty work environment modelling in BowTieXP Software.

Discussion and Results

As a result of risk matrix analysis, "Stock area and work environment" risk is found to have the highest risk score, which is 16 points. According to this result, bowtie analysis is carried out for the risk (Figure 4). Proactive and reactive precautions are defined for "Stock area and work environment" risk. Duijm (2009), Limerick et al. (2014), Pitblado and Weijand (2014), Saud et al. (2014), and Kozyrev et al. (2018) study the probability of important risks are decreased using bowtie analysis. Similarly, in this study, bowtie analysis decreases the probability of "Stock area and work environment" risk, which is one of the important risks for surface plants of mines. Among the proactive measures, stable geometry of the stock area and air isolation take the first place (Figure 6). The geometry of stock should be arranged according to the properties of the ore. Air isolation is especially important in coal mining and metallic ore mining in order to prevent fire and oxidation, respectively. In addition, the prevention of insufficient lighting is important, especially during nighttime shifts (Figure 7). In order to do so, lamps on the lighting columns should be controlled regularly and changed if necessary (Figure 1 - Number 20).

Also, it can be seen from Figure 8 that maintenance and control of the crane and rope are among the other proactive barriers to prevent serious accidents. Finally, dust is another important risk in the work environment (Figure 9). Removing dust from the work environment is vital to prevent pneumoconiosis disease in employees. In addition, dust should also be removed in order not to cause damage to machinery and equipment. Therefore, the work environment should be kept clean, and the health quality of the workplace should be increased.

On the other hand, reactive measures for "Stock area and work environment" risk can also be seen in Figure 5. Fire alarm systems and fire extinguishers are necessary in order to decrease the effect of a fire in the stock area. In case of a collision, emergency lighting and a generator should get in use. Work area isolation and emergency brakes would be useful for rope-braking accidents. Finally, in order to decrease the effects of occupational illnesses, dust masks must be used, and medical checks should be done regularly.

Conclusion

Risk analysis should be considered when establishing surface plants in mines to provide workplace safety and health. In this study, the potential risks of a surface plant are identified and analyzed using the risk matrix method. As a result of the risk matrix, stock area and work environment, natural events, working at high levels, explosives and electricity risks are found to be important risks. Then, the highest priority risk, which is found to be "Stock area and work environment", is considered using bowtie analysis. Proactive and reactive measures are defined in order to decrease the risk priority. During the operation of the mine, it is also important to manage this risk. Four threats are determined for "Stock area and work environment" risk. These are improper ore or coal stock area, insufficient lighting in night works, lack of maintenance field crane and dusty work environment. These threats are also modelled using bowtie analysis. As a result of this study, safety and operational engineers can manage these threats, corresponding barriers and consequences. In addition, the proposed methodology integrating risk matrix and bowtie analysis is a fast and effective procedure for risk assessment. It can also be applied in other industries.

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