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Application of Bowtie Analysis Risk Assessment Tool and Layer of Protection Analysis (LOPA) to Reduce Fire Incidents in Heavy Equipment during Mining Operations

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ABSTRACT:
The mining industry is an industry that involves a significant amount of heavy equipment in production activities. This heavy equipment is used to facilitate mining activities by speeding up the production process and reducing risks in production activities. During the operational period in 2022, one of the mining companies faced challenges in its operational activities. Favorable commodity prices and increasing demand for coal made it difficult for operational activities to meet these needs. This situation was not supported by the readiness of operational units to face these challenges. There have been various incidents of heavy equipment fires in mining operations, which have resulted in operational disruptions and financial losses for the company. To prevent these losses, an analysis was conducted using Bowtie Analysis and Layer of Protection Analysis (LOPA). Bowtie Analysis is a technique that utilizes a bow tie-shaped diagram to represent risk events in a simple term. This method aims to provide a comprehensive overview (helicopter view) of the logical sequence of various risk event scenarios and offers a clear visual explanation of the connections between risk events, their causes, and their potential consequences. Layer of Protection Analysis (LOPA) is a tool used to understand how a process deviation or change can lead to major accident hazards. From the analysis results, 17 solutions were identified to address the root cause of the problem. These 17 solutions were then implemented in operational activities, and the results were monitored to assess their effectiveness. It was reported that heavy equipment fire incidents in mining areas decreased from 16 incidents to 3 incidents. In percentage terms, the reduction in heavy equipment fire incidents was 81,25%. Additionally, there was an increase in production capacity by 0,42 milion tons compared to the previous year
Keywords: Bow Tie, Fire Incidents, LOPA, Mining

INTRODUCTION

PT X is a company operating in the energy and mining sectors. As one of the leading coal suppliers for domestic and international markets, PT X conducts its mining operations in South Kalimantan Province, Indonesia. During the operational period in 2022, PT X faced significant challenges in its activities. Favorable commodity prices resulted in increased demand, placing operational activities under pressure to meet these requirements. However, this situation was not supported by the readiness of operational units to address these challenges effectively. Throughout 2022, there were 16 incidents of production units catching fire in the mining area, causing operational disruptions and financial losses for the company (Figure 1). The investigation into incidents of production unit fires revealed that the causes were highly varied and originated from multiple sources. The factors contributing to these incidents in mining areas included, among others: poor cable installation, inadequate protective measures, oil leaks, insufficient maintenance systems, and various other issues. In recent years, the exploration of the causes of production unit fires has largely focused on post-incident investigations and recommendations for corrective actions. This approach resulted in corrective actions that primarily focused on addressing the causes of fire incidents without sufficiently implementing systematic improvements or preventing recurrence. To eliminate operational disruptions, a more in-depth investigation into production unit fire incidents was conducted using Bowtie Analysis and Layer of Protection Analysis (LOPA) techniques. This study aims to identify more specific causes of production unit fires in mining areas, develop more systematic prevention and mitigation measures, and draw conclusions with actionable recommendations for future improvements.

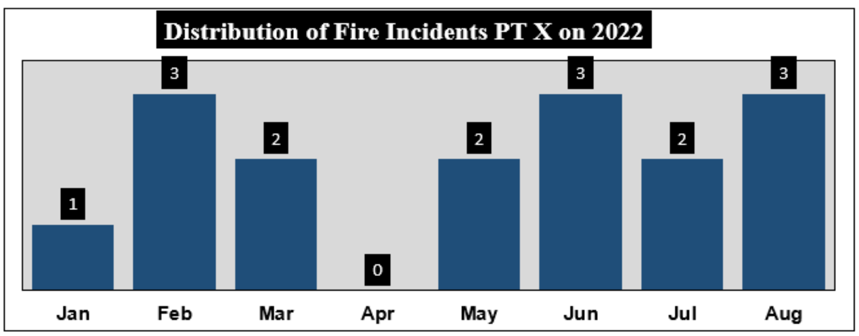

Figure 1 Distribution of Fire Incidents in PT X in 2022

RESEARCH METHODS

The ‘bow-tie’ diagram is a practical risk management tool that provides a visual representation of the relationships between hazards, initiating events, controls, and consequences. It is easily understood by various stakeholders, including management, engineers, OHSE (Occupational Health, Safety, and Environment) professionals, process operators, and maintenance personnel involved in risk management. This method facilitates a systematic approach to identifying potential risks and determining effective control measures (Figure 2). Additionally, rapid risk ranking methods are often utilized to evaluate risks by analyzing simple likelihood-consequence pairs [1].

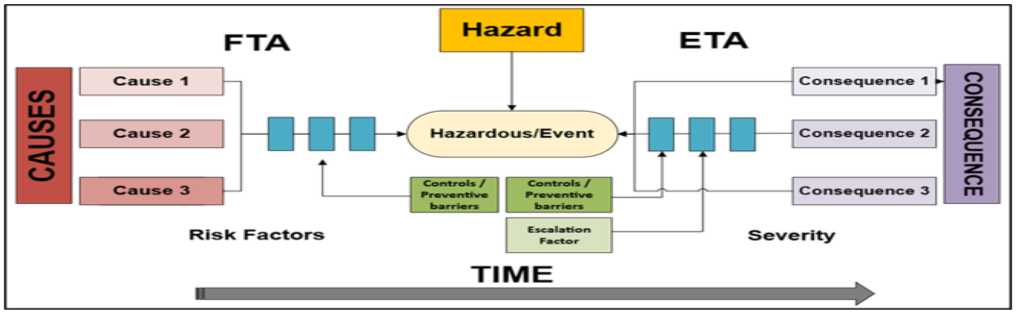

Figure 2 Typical Representation of a Bowtie Diagram

Bow Tie concept generally guides companies in determining risk controls by focusing efforts on preventing incidents and mitigating the severity of consequences if incidents occur. Preventive measures focus on implementing appropriate steps to address potential incidents and prevent them from happening. Mitigation actions, on the other hand, guide companies in establishing control measures aimed at reducing or mitigating the severity or consequences of incidents [2]. A significant number of researchers have directed their attention to the Bow Tie method. Some of these studies have concentrated on industry domains such as mining, chemical and process industries, and oil and gas sectors. Meanwhile, other researchers have applied the Bow Tie method to fields like IT, risk management, and risk assessment [3, 4, 5].

Data

The data used in this study consisted of fire incident incidents involving production units in the mining area of PT X during 2022. The collected data included findings from accident investigations conducted by the investigation team, supplemented with additional supporting data

Data Processing

Data processing was carried out by analyzing several investigation reports on fire incidents involving production units. To deepen the understanding of the causes of these fires, interviews were also conducted with witnesses involved in the incidents. The collected data was then organized into tables to identify management failures in each process.

It was found that the highest cause of production unit fire incidents was due to the electrical system at 37.5%, followed by engine issues at 31.3%, poor maintenance at 18.8%, and fuel leakage at 12.5% (Table 1).

Table 1 Distribution of Root Causes Based on Investigation

No	Root Cause	Number of Incidents	Percentages
1	Electrical System	6	37,5%
2	Engine Issues	5	31,3%
3	Poor Maintenance	3	18,8%
4	Fuel Leakage	2	12,5%
	Total	**16**	**100%**

Layer of Protection Analysis (LOPA)

LOPA (Layer of Protection Analysis) is a tool used to understand how a hazard resulting from a process deviation or change can escalate into a major accident hazard (MAH) with severe consequences, while protective measures are implemented to prevent such outcomes [6]. To prevent fire incidents, multiple protection layers are typically applied. There are seven layers of safety related to process safety, encompassing both design and operation. Without proper management and hazard prevention, these risks can escalate, necessitating additional external protection layers to mitigate them (Figure 3). The lowest level of protection is the process design itself, or more specifically, an inherently safer design (ISD) [7]. To prevent production unit fires, PT X had previously implemented several layers of protection designed to mitigate the risk of fire incidents in the mining area. These layers are illustrated in Figure 4. This layer is designed to align with appropriate controls that can be implemented in production units within the mining area. The target of this study is to reduce the number of production unit fire incidents in the mining area from 16 incidents to 0 incidents. This is achieved by identifying potential fire sources using Bowtie Analysis and Layer of Protection Analysi

Contructing the Bowtie Model

There are several stages involved in constructing a Bowtie model, as illustrated in the Figure 5. These stages include identifying hazards, analyzing their causes, identifying escalation factors, and determining preventive measures. The Bowtie construction process involves collaboration with various stakeholders, including practitioners and academics. Additionally, benchmarking was conducted across different companies to observe best practices that could be implemented. The results were then presented in the Bowtie diagram form, as shown in Figure 5.

Combine the FTA and ETA into Bowtie Diagram

Fault Tree Analysis (FTA) is a top-down, deductive method used to analyze the causes of system failures. Within the Bowtie context, FTA is often employed to identify initiating events represented on the left side of the Bowtie diagram. Fault trees help trace the propagation of failures and uncover root causes that might lead to specific risk events. Event Tree Analysis (ETA), on the other hand, is an inductive method used to explore the potential consequences or outcomes of an initiating event. ETA analyzes how an initial failure or incident might lead to various possible outcomes, which are represented on the right side of the Bowtie diagram. The integrated outputs of FTA and ETA were used to conduct further risk analysis, providing a comprehensive overview from the root causes of initiating events to their consequences and impacts on people, the environment, assets, and reputation. Preventive and mitigative barriers were presented in the Bowtie model as additional risk control measures [6].

Multivariable/Multiple Linear Regression (MLR)

Multiple correlation analysis is an extension of simple correlation analysis. The purpose of multiple correlation analysis is to determine the degree of relationship between several independent variables (X1, X2, ..., Xk) and a dependent variable (Y) simultaneously [8]. The assumptions related to multiple regression analysis are as follows:

1. Independent variables and the dependent variable have a linear relationship
2. All variables, both independent and dependent, are continuous random variables.
3. The conditional distribution of each variable follows a normal distribution (multivariate normal distribution)
4. For various combinations of values between one variable and another, the variance of the conditional distribution of each variable is homogeneous (the assumption of homoscedasticity applies to all variables)
5. For each variable, the observations are independent of one another.

Based on multiple correlation, denoted as RY.12…n , it is calculated through the pathways of the relationship between several independent variables (X1, X2, …, Xn) and a single dependent variable (Y). This relationship is represented by a multiple linear regression equation:

$$Y' = a + b_1.x_1 + b_2.x_2 + \cdots \dots . + b_n.x_n \qquad (1)$$

Based on the multiple regression, the multiple linear correlation coefficient is calculated using the following formula:

$$\sqrt{\frac{b_1 \sum x_1 Y + b_2 \sum x_2 Y + \cdots \dots + b_n \sum x_n Y}{\sum Y^2}} \qquad (2)$$

Fire Safety Audit

Fire Safety audit is an examination of the hypothetical and useful documents to discover how the premises are being managed concerning fire safety. Specifically, a fire safety audit is a comprehensive, well-structured, and systematic evaluation that helps an organization identify all possible fire hazards. It evaluates components, services, and equipment and provides recommendations to ensure regular compliance with existing building codes, rules, standards, and regulations. A fire safety audit identifies any non-compliance or specific fire safety risk issues. Upon completing the audit, recommendations are provided to address the identified deficiencies, ensuring that the building and its systems comply with relevant legislation. Fire Safety Audits play a crucial role not only in mitigating fire hazards but also in significantly reducing uncertainties.

Fire safety is a key aspect of industrial safety audits. It primarily involves:

a. Fire safety awareness training for employees
b. Emergency exit plan

c. Fire safety management
d. Fire drills
e. Do's and Dont's in case of fire
f. Ventilation, sprinkler and emergency lighting system

The findings of a fire safety audit are documented in a detailed report that includes recommendations for addressing any identified non-compliance. These reviews highlight remedial actions, which play a vital role in improving overall safety [9]. Conducting periodic fire safety audits helps to Prevent property loss, protect human lives, ensure ongoing compliance with safety standards, and continuously identify and address areas for improvement. By systematically evaluating fire safety measures and implementing corrective actions, fire safety audits greatly contribute to creating safer environments in both industrial and non-industrial settings.

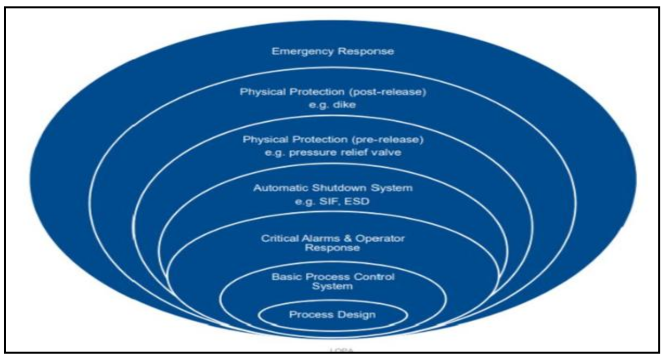

Figure 3 Layers of Protection Analysis (LOPA) in order to prevent fire and explosion

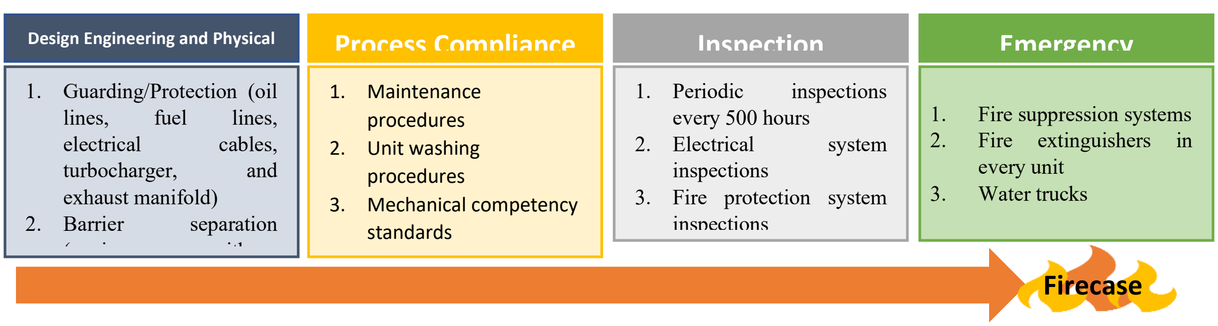

Figure 4 Layer of Protection for Fire Incidents

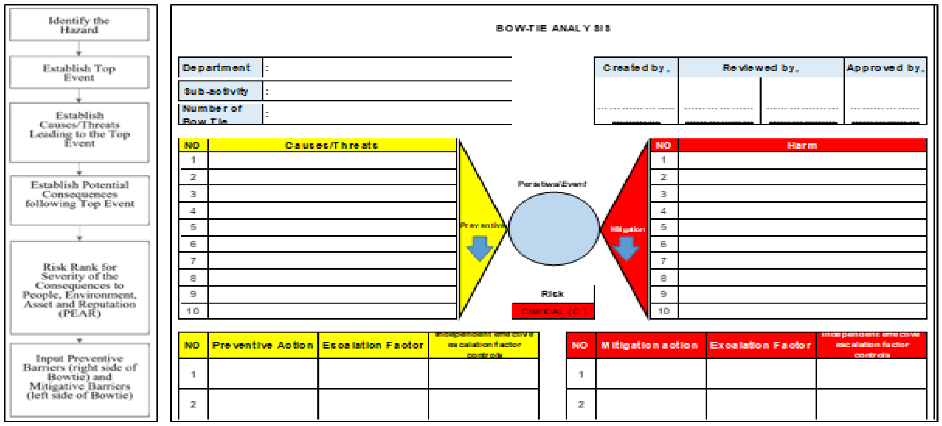

Figure 5 Bowtie Flow Process

RESULTS AND DISCUSSION

From the Bowtie diagram, it can be observed that several additional preventive and mitigative actions must be implemented to avoid fire incidents in production units within the mining area. Furthermore, effective and independent controls for escalation factors were established to improve the quality of the preventive and mitigative measures implemented.

Quantitative Analysis

To analyze the relationship between failures across protection layers, a multiple correlation test was conducted. This method aims to evaluate the strength of simultaneous relationships between two or more independent variables (X) and a dependent variable (Y). The variables used to test the relationships at each layer are summarized in the following data table.

The criteria for decision-making are as follows:

a. If Sig. F Change < 0,05, the variables exhibit a significant correlation.
b. If Sig. F Change > 0,05, the variables do not exhibit a significant correlation.

Based on the guideline for interpreting the degree of relationship using the Pearson Correlation coefficient, the analysis revealed a moderate correlation. This indicates that the relationship between variables X1, X2, X3, X4, and Y falls within the moderate correlation category.The initial hypotheses for this analysis are defined as:

a. H0: There is no association between protection layers.
b. H1: There is an association between protection layers.

The results of the multiple correlation test, processed using SPSS software, show an α value of 0,044. Since this value is below the threshold of 0,05, it can be concluded that H0 is rejected, and H1 is accepted (Table 2). This signifies that there is a statistically significant correlation between the layers, indicating that failures in one layer have an impact on the likelihood of failures in other layers.

Table 2 The results of the multiple correlation test

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.510[a]	.260	.207	.640	.260	4.924	1	14	.044

a. Predictors: (Constant), Emergency

Qualitative Analysis

Various data on the causes of production unit fire incidents in the mining area were added to the "causes" column in the Bowtie diagram, located on the left side of the diagram. Each cause was then analyzed using the Fault Tree Analysis (FTA) method to identify its root causes. The analysis revealed five root causes of production unit fire incidents in the mining area (Table 3). Once the root causes were identified, appropriate preventive actions were developed to address these issues (Table 4). To ensure the consistency of preventive actions, procedures were established to regulate and guide the proper implementation of these measures. These actions were done in accordance with the analysis of escalation factors that were identified. A brainstorming session was conducted involving various stakeholders to determine appropriate preventive actions for each root cause. An analysis of the escalation factors for each preventive action was also carried out. By identifying these escalation factors, effective and independent controls for the escalation factors could be established.

The next analysis focuses on the consequences/losses resulting from production unit fires. Various data on the causes of losses were analyzed and presented in the right-hand column of the Bowtie diagram. The loss analysis was conducted using Event Tree Analysis (ETA). The analysis identified three types of losses that would occur in the event of a fire in production units within the mining area (Table 5). The results of the analysis in Table 5 highlight the mitigation actions implemented to prevent greater losses. These mitigation actions are intended to reduce or eliminate losses if preventive measures fail. The mitigation actions are also designed with consideration for their effectiveness and the speed of implementation to prevent broader impacts (Table 6).

After that, the results of the analysis using the Bowtie diagram were subsequently added to the existing layers of protection (Figure 6). This aims to develop and strengthen the existing layers of protection based on the previous Layer of Protection Analysis (LOPA). Various preventive and mitigative actions were introduced to reinforce the protection system and prevent the escalation of losses caused by production unit fires in the mining area. From the perspective of design engineering, three additional controls were identified as necessary. In terms of process compliance, four additional controls were required. To improve inspection quality, six additional controls were added to the protection layers. Lastly, for mitigation actions in the emergency layer, four additional controls were implemented.

These additional preventive and mitigative actions are periodically reviewed through a Fire Safety Audit. The audit involves reviewing the consistency of the implementation of preventive and mitigative actions. It is expected that any shortcomings in the execution of these actions will be identified during the audit and promptly addressed with comprehensive improvements. After implementing the preventive and mitigative actions, the number of production unit fire incidents in the mining area decreased to only 3 incidents in 2023. This reduction represents a percentage decrease of 81.25% (Figure 7). In addition to the decrease in production unit fire incidents in the mining area, the corrective and mitigative actions taken also had a positive impact on coal production in 2023. Production increased by 0.42 milion tons. This improvement was due to the absence of production time lost caused by production unit fire incidents (Figure 8)

Table 3 Root Causes Based on Fault Tree Analysis

NO	Causes/Threats
1	Failure of protection of the electrical system
2	Hot turbocharge & exhaust manifold
3	Cooling system failure on turbocharger
4	Fuel leakage
5	Coal dust in the engine room

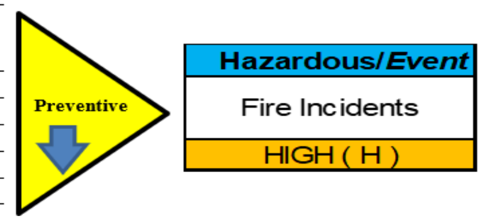

Table 4 Preventive Actions Based on Bowtie Analysis

NO	Preventive Action	Escalation Factor	Independent Effective Escalation Factor Controls
1.1	Installing clamps on the wiring harness and *Kawashima* wiring harness	Not all wiring harnesses have clamps installed	Standardization of wiring harness and clamp circuits
		The wiring harness is exposed to friction on the part where the clamp is not attached.	Installing a guard on the wiring harness
2.1	Turbocharge and exhaust manifold suitability inspection	Excessive heat in the turbocharger and an unidentified exhaust manifold leak	Installing a thermal blanket on the turbocharger and exhaust manifold
3.1	Checking the radiator coolant level warning system (buzzer) during the Periodical Inspection (PI)	The check of the radiator coolant level warning system (buzzer) is not detailed in the checklist	Ensuring the fulfillment of competent mechanical personnel
4.1	Oil/fuel hose suitability inspection	incompetent inspector	Ensuring the fulfillment of competent inspectors.
		The inspector does not have the knowledge to check the hose condition	Assigning specific personnel to carry out inspections.
			Conducting training and socialization on critical items

NO	Preventive Action	Escalation Factor	Independent Effective Escalation Factor Controls
			during periodic inspections for all Operators, Mechanics, and Supervisors, especially new employees.
		Inspection is not detailed or not all parts can be inspected	Checking the condition of the hose, especially under the bottom of the control valve, by opening the bottom guard during each Periodic Service
5.1	Regular unit washing every 2 days	Washing was not done optimally due to lack of time	Creating effective washing time standards
		Not all parts are washed.	Revising washing procedures, including those for subcontractor

Table 5 Consequences / Harm Based on Bowtie Analysis

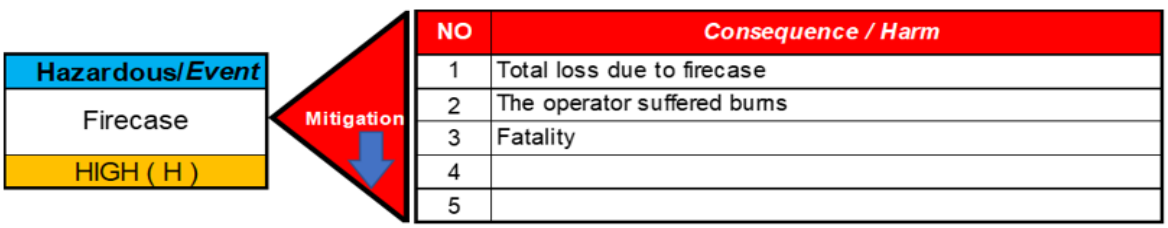

Table 6 Mitigation Actions Based on Bowtie Analysis

NO	Mitigation Action	Escalation Factor	Independent Effective Escalation Factor Controls
1.1	Fire Suppression Installation	Fire Suppression is not working properly.	Conduct regular fire suppression system checks.
		Fire Suppression does not reach areas of the unit that are prone to fire.	Redesign the coverage path of the fire suppression system.
1.2	Fire extinguisher installation	The fire extinguisher is not working.	Conduct fire extinguisher inspections during pre-operation checklists.
		The operator does not know how to use a fire extinguisher	Provide basic firefighting training for operators
		Fire extinguisher unable to extinguish the fire	Allocate a water truck to assist in extinguishing fires
2.1	Fast and precise response in handling unit fires	Mechanics, operators, and supervisors are less aware and do not respond correctly when the unit catches fire.	Conduct awareness training and emergency drills on unit fire risks for

NO	Mitigation Action	Escalation Factor	Independent Effective Escalation Factor Controls
			operators, mechanics, and supervisors.
2.2	Emergency Incident Reporting and Handling Flow Chart	The operator or direct supervisor does not understand the flow of reporting emergency incidents	Refresh the Emergency Incident Reporting and Handling Flow during the reinduction process

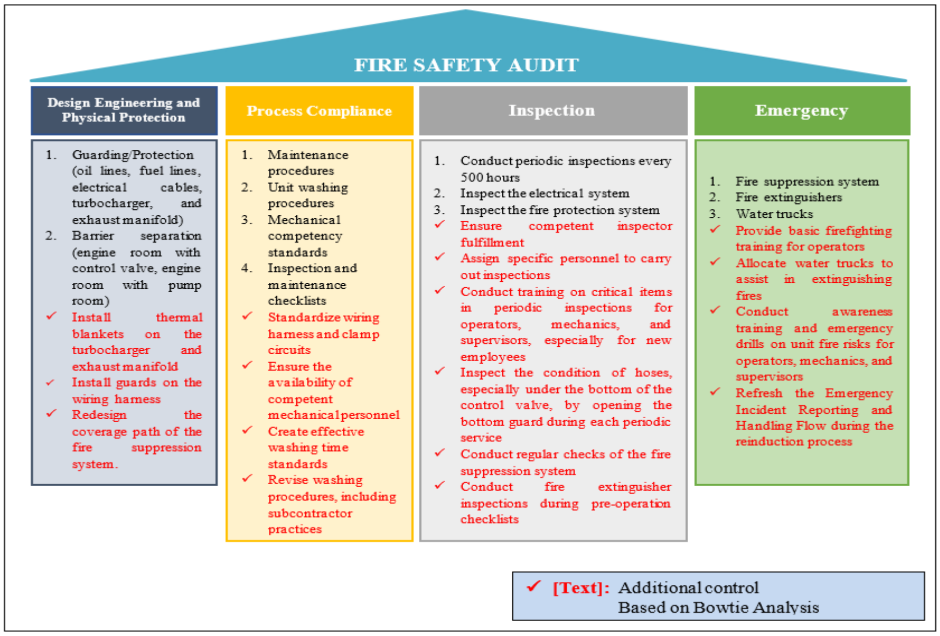

Figure 6 LOPA After Analysis Using the Bowtie Diagram

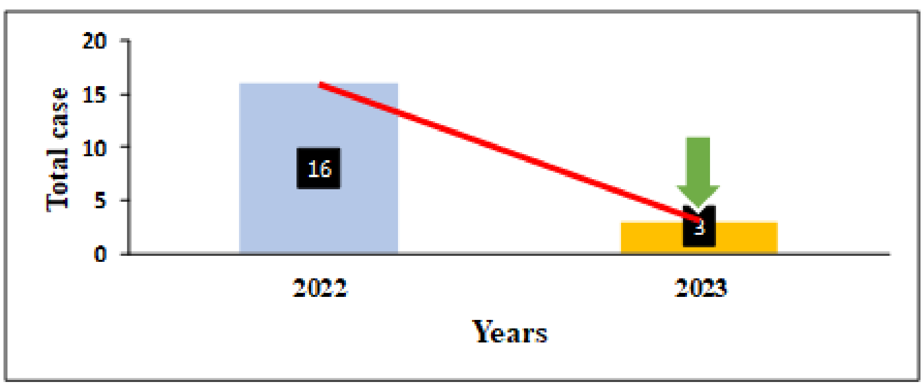

Figure 7 Comparison of Production Unit Fire Incidents in the Mining Area After the Implementation of Bowtie Analysis and LOPA

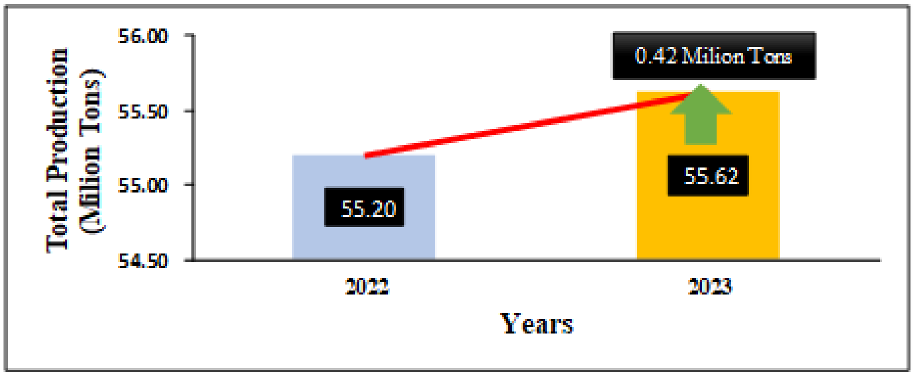

Figure 8 Comparison of Total Production in the Mining Area After the Implementation of Bowtie Analysis and LOPA

CONCLUSION

The implementation of Bowtie Analysis and LOPA has had a positive impact on several aspects of mining operations. This is evident in Table 7, which shows the conditions before and after applying Bowtie Analysis and LOPA Improvements in the five aspects of operational activities have positively impacted the company's operations, enabling it to meet the increasing demand for coal supply over time

Table 1 Comparison Before and After the Improvements of Bowtie Analysis and LOPA

ASPECT	BEFORE	AFTER IMPROVEMENTS
QUALITY	The quality of unit repair work did not ensure the unit was completely safe for use. Physical Avaibility (PA) 90%	The quality of unit repair work ensures the unit is safe for use. Physical Avaibility (PA) 92%
COST	High accident costs, with direct costs of USD 1,592,912.72 and indirect costs of USD 52,228.01.	Losses from unit fire accidents decreased from direct costs of USD 1,592,912.72 and indirect costs of USD 52,228.01 to USD 0.
DELIVERY	The information about the causes of production unit fires in the mining area was not clearly known.	The information about the causes of production unit fires in the mining area is now clearly known.
SAFETY	There were 16 incidents of production unit fires in 2022.	A reduction of production unit fire incidents by 81.25%.

PRODUCTIVITY	• Coal production was 55.2 milion tons. • Overburden production was 191.82 milion BCM	• Coal production increased by 0.42 milion tons. • Overburden production was 219.38 milion BCM

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