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Risk Identification and Decision-Making in Low-Rank Coal Handling: FMEA-AHP

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Abstract

Purpose: This study addresses the challenges posed by the increasing proportion of lower-ranking coal through proactive risk management in the Coal Preparation Plant (CPP) area of the PT. XYZ. Previous failures in handling lower-ranking coal have led to production delays and have negatively impacted the coal handling process. The analysis focuses on identifying, assessing, and prioritizing risks, and formulating optimal solutions to minimize their impact.

Method: The methodology incorporates FMEA for risk identification and ranking, and proposes the top three risks and alternative solutions. Then, it proceeds with The Analytic Hierarchy Process (AHP), guided by criteria from Value-Focused Thinking (VFT), to determine the most optimal solution.

Results: The top three identified risks and their corresponding solutions are as follows: (1) sticky material adherence to the drawdown hopper and chute wall causing material flow blockage and overfill, addressed by installing a booster pump on the existing water suppression system. (2) The accumulation of fine coal in closed spaces causes equipment burning, mitigated through periodic clean-up using a new portable blower or water. (3) Burning coal, causing fires inside the tunnel, was resolved by installing a thermal camera monitoring system.

Conclusions: The study concludes that the handling of lower-ranking coal within the CPP area presents several critical risks primarily associated with excessive airborne coal dust, sticky materials, and fine coal accumulation. Airborne dust reduces visibility, posing safety hazards and health risks, while also interfering with sensors and contaminating nearby equipment. Sticky materials adhering to chutes and conveyors cause blockages, overfills, belt drift, and trigger false sensor alerts, significantly reducing operational efficiency.

Limitations: The scope of the research will be limited to the specific area of the Coal Processing Plant (CPP) in the company and will be based on the characteristics of the lower-ranking coal in the company.

Contributions: This study provides valuable guidelines for CPP stakeholders to minimize disruptions and improve the overall effectiveness of coal-handling activities.

Keywords: *Analytic Hierarchy Process (AHP), Coal Handling Activities, Failure Mode Effect and Analysis (FMEA), Proactive risk management.*

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1. Introduction

The mining process at the PT. XYZ was carried out using trucks and shovels using an open-pit method. After being exposed in the mining area, the coal is transported to the coal handling facilities, which include the Coal Preparation Area (CPP) and the Coal Terminal Area (CT). In general, the process at coal handling facilities includes crushing, transportation by belt conveyor, stockpiling/stacking, and reclamation of coal products.

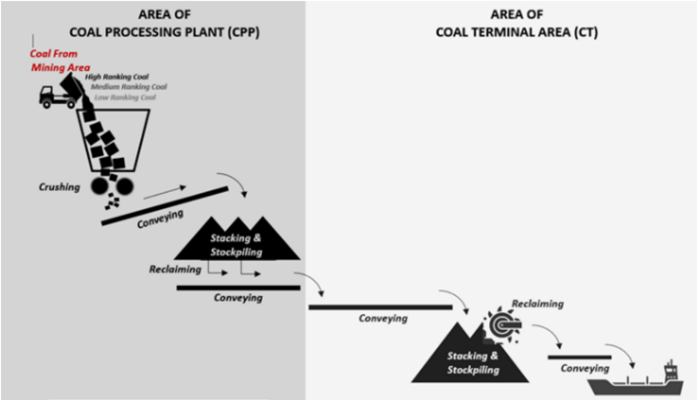

Figure 1. Coal-handling activities in the PT. XYZ
Source: company internal data

Typically, coal intended for thermal use is marketed based on its as-received calorific value. It uses the calorific value per mass (MJ/kg, kcal/kg) as the unit of measurement. The as-received calorific value was influenced by the moisture and ash contents of the coal. Higher moisture and ash levels result in lower calorific values. Currently, there is an increasing proportion of lower-ranking coal in PT. XYZ, which is causing concern, particularly in coal handling facilities, as shown in Figure 2 (with the lower-ranking coal being Product III).

Over the past few years, a series of events has disrupted the coal-handling process, specifically related to dealing with lower-ranking coal. One of the significant impacts was caused by a fire in the reclaimed system in the area, resulting in a production delay of three days. Another recent incident occurred in the stacking system of the CPP area, leading to a production delay of 12 h. In addition to major production delays, the presence of lower-ranking coal, particularly as a blockage material, has frequently caused delays lasting several hours. A company's internal investigation revealed that lower-ranking coal was one of the contributing factors to these incidents.

Table 1. Major Incidents Caused During Handling Lower Ranking Coal

Date	**Incident Summary**	**Production restoration cost (USD)**	**Production delay (hours)**	**Production loss of coal (ton)**
Feb-2023	The conveyor belt burned due to spontaneous combustion of coal while it was stopped.	374,000	45 hours	135,000
Aug-2023	Conveyor CV02 Tripper belt tracking caused the belt flipped	5,000	12 hours	36,000

Source: Company Internal Data (2024)

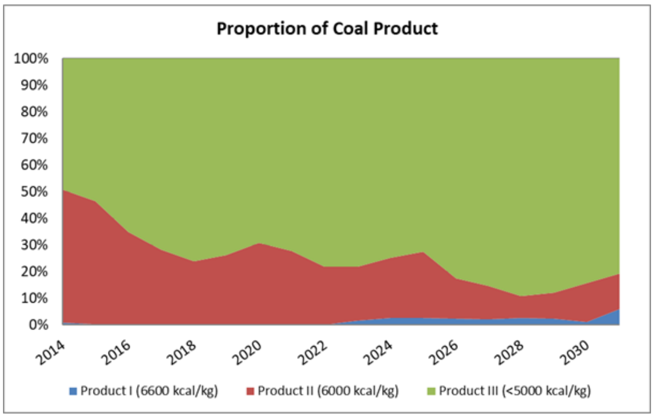

Figure 2. Proportion of coal products PT. XYZ
Source: company internal data

To minimize the probability of future disruptions in coal handling activity, it is crucial to proactively identify, prioritize, and manage other risks that may arise during the handling of low-ranking coal.

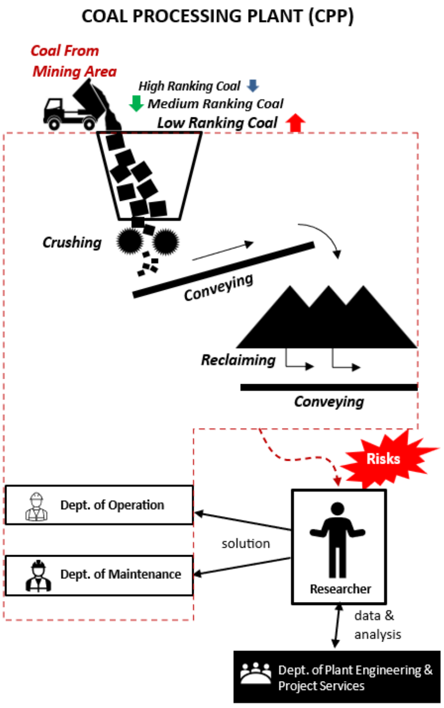

Figure 3. Rich Picture and Limitation of the Study
Source: Author

The scope of the research will be limited to the specific area of the (CPP) in the company and will be based on the characteristics of the lower-ranking coal in the company.

2. Literature review

2.1 Cynefin Framework

Cynefin is a decision-making framework that is applicable to organizations, systems, and complex social environments. The structure encompasses the system categories of ordered (Simple and Complicated), Complex, and Chaotic. At the center of these four systems, a fifth domain called disorder was introduced, completing the structure of the cynefin framework.

Table 2. Cynefin Framework Table

Complexity	Characteristic	Approach	Practice
Clear/Simple	The connections between cause and effect are obvious, can be predicted and repeated, and typically follow a linear pattern.	sense-categorise-respond	Implement best practice
Complicated	There exists rational connection between cause and effect, yet it is not immediately clear and required expert analysis to understand.	sense-analyse-respond	create panel of experts
Complex	Only apparent after the fact, with outcomes that are unpredictable.	probe-sense-respond	experiments that allow patterns to emerge
Chaotic	No relation between cause and effect	act-sense-respond	explore new methodologies.
Disorder	The context to which a situation should be allocated is unclear.		

Source: Puik and Ceglarek (2015)

2.2 FMEA (Failure Mode Effect Analysis)

The FMEA is an approach used to examine the potential failure modes of individual subsystems within a system and assess their corresponding consequences. This inductive analysis categorizes each failure mode to pinpoint crucial risk events, thereby providing guidance for risk prevention and control. Widely acknowledged as a straightforward and highly efficient technique, FMEA is particularly valuable for proactively preventing issues and retrospectively enhancing reliability (Liu, You, Ding, & Su, 2015).

The FMEA method assesses the risk associated with failure modes through the mathematical multiplication of three parameters: O (occurrence), S (severity), and D (detection). The output is then stated as the (RPN) the following equation:

$$RPN = O \times S \times D$$

The prioritization of risks is based on RPN values, where a higher RPN value signifies a greater need for prioritized attention. An elevated RPN value corresponds to increased system risk, making higher RPN values more critical to the overall system (Goksu & Arslan, 2023). The definitions of the likelihood of occurrence (O), severity (S), and non-detection (D), as adopted from Ahmed and Gu (2020), are presented in the tables below, with the adjustment referring to the internal company's risk assessment guidance.

Table 3. Scoring Guidance for Occurrence (O)

Score	Occurrence (failure probability)	Linguistic Terms
1	Unlikely in life of mine	Very Low
2	Once in 15 years	Low
3	Once in 10 years	Low
4	Once in 5 years	Low
5	Once in a year	Medium
6	Twice in a year	Medium
7	Six times in a year	High
8	Once in a month	High
9	Once in a week	Very High
10	Once in two days	Almost certain

Source: Ahmed and Gu (2020)and company internal data

Table 4. Scoring Guidance for Severity (S)

Score	Severity (Duration of Production Delays)	Linguistic Terms
1	No impact on operation	Very Low
2	Less than 15 minutes	Low
3	Less than 30 minutes	Low
4	Less than 60 minutes	Low
5	Less than 3 hours	Medium
6	Less than 6 hours	Medium
7	Less than 1 shift (12 hours)	Medium
8	1-4 shifts production delay	High
9	1-3 days production delay	High
10	3-6 days production delay	Very High

Source: Ahmed and Gu (2020)and company internal data

Table 5. Scoring Guidance for Non-Detection (D)

Score	Non-Detection	Linguistic Terms
1	Extremely unlikely that controls will fail to detect probable cause and its subsequent failure mode.	Very Low
2	Very unlikely chance that controls will fail to detect probable cause and its subsequent failure mode.	Low
3	Unlikely chance that controls will fail to detect probable cause and its subsequent failure mode.	Low
4	Very low probability that controls will fail to detect probable cause and its subsequent failure mode.	Low
5	Low probability that controls will fail to detect probable cause and its subsequent failure mode.	Medium
6	Moderate probability that controls will fail to detect probable cause and its subsequent failure mode.	Medium
7	Moderately high probability High probability that controls will fail to detect probable cause and its subsequent failure mode.	High
8	High probability that controls will fail to detect probable cause and its subsequent failure mode.	High
9	Very high probability that controls will fail to detect probable cause and its subsequent failure mode.	High
10	Controls will certainly fail to detect probable cause and its subsequent failure mode.	Very High

Source: Ahmed and Gu (2020)

2.3 Value Focus Thinking

Value-focused thinking is a decision-making approach that comprises two fundamental activities. The initial step involves determining and defining preferences, and understanding what is important or valuable. The second step involves formulating a strategic plan to achieve desired outcomes. The more conventional method, known as alternative-focused thinking, involves identifying and exploring the various available options or alternatives (Keeney, 1996). For this study, a modified VFT (Françozo & Belderrain, 2022) was used. This approach is more systematic and involves fewer steps while retaining the core concept of Value-Focused Thinking (VFT). The steps are as follows; Step 1: Identify values because thinking about them is the central point of the VFT. The most appropriate method for performing this step is to compose the goal. Step 2: Express the values from the wish list in verb+object format to clearly articulate intentions and transform them into tangible objectives. In this step, it is also possible to group multiple wish lists into one category; conversely, one wish list can be divided into multiple objectives.

1. Step 3: Defining connections to establish an objective hierarchy involves categorizing objectives into a hierarchical structure. Some objectives serve to achieve others, forming what is known as means-objectives, with the final objectives at the top of the hierarchy termed fundamental objectives.
2. Step 4: The final stage involved constructing a means-end objective network. Visual representation offers a rapid overview of intentions within a problematic situation and illustrates the relationships between objectives.

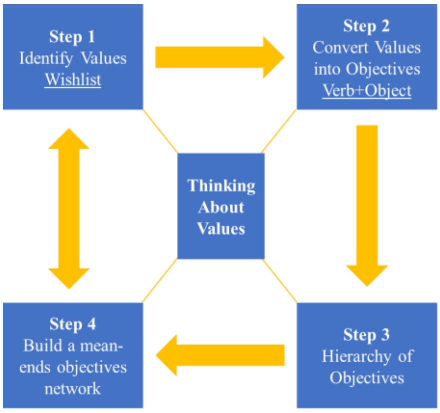

Figure 4. Systematic Value Focus Thinking
Source: Françozo and Belderrain (2022)

2.4 Analytical Hierarchy Process (AHP)

AHP is a decision-making process that is defined as "*an approach to decision making that involves structuring multiple choice criteria into a hierarchy, assessing the relative importance of these criteria, comparing alternatives for each criterion, and determining an overall ranking of the alternatives*" (Decision Support Systems Resources Glossary). AHP is a technique applicable for formulating metrics in both physical and social dimensions. The physical dimension relates to what is commonly referred to as tangibles, involving some form of objective reality external to the individual undertaking the measurement. On the other hand, the psychological dimension involves intangibles, including subjective concepts and beliefs held by the individual about oneself and the world of experience (R. W. Saaty, 1987). The AHP process includes the following steps:

a. Structure a hierarchy that represents the problem in terms of the goal, determines the criteria or attributes, and identifies alternatives.

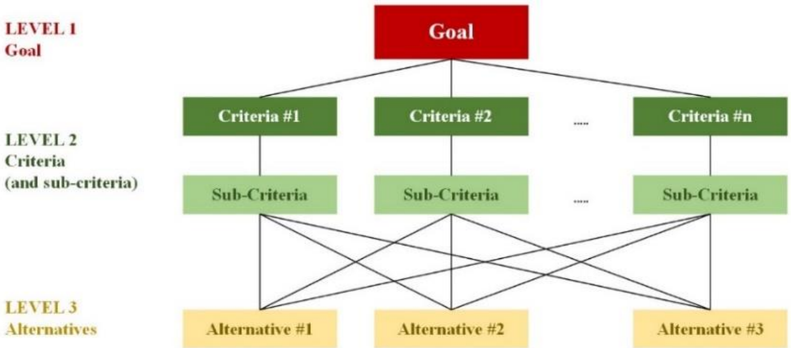

Figure 5. Hierarchy of Goal, Criteria, and Alternatives
Source: Author

b. Establish a rating system for pairwise comparisons and make pairwise comparisons. The relative importance between each pair of decision alternatives and criteria is assessed based on the value of the rating system.

Table 6. Rating System for Pairwise Comparison

Rating	Definition	Remarks
1	Equal preference	Both items equally contribute to the goal.
3	Moderate preference of one over the other	One activity is moderately preferred over the other.
5	Essential or strong preference	One activity is strongly preferred based on experience and judgment.
7	Very strong preference	The dominance of one activity is evident through strong preference.
9	Extremely preference	The evidence affirming one activity's advantage is of the highest level.
2, 4, 6, 8	Intermediate values between adjacent judgments	In situations requiring a compromise.

The relative importance between each pair of decision alternatives and criteria is assessed based on the value of the rating system. Because multiple respondents contribute to the pairwise comparison process, the geometric mean is used instead of the arithmetic mean to combine local pairwise comparisons with global ones. The geometric mean has advantages in maintaining consistency, reliability, and independence from normalization conditions for accuracy and stability in the AHP (Krejčí & Stoklasa, 2018).

The synthesis procedure involves summing the column values from the pairwise comparison, normalizing them so that each column adds up to one, and averaging the rows to convert them into decimal form, resulting in a priority vector representing the relative importance of options. A consistency check, for an instance commonly observed in pairwise judgment surveys, is when the participant expresses a preference for criterion #1 over criterion #2, criterion #2 over criterion #3, and criterion #3 over criterion #1.

The Consistency Ratio within the AHP serves as a measure of consistency in respondents' judgments. When the results of the judgments are perfectly consistent, the consistency ratio is zero. This reflects the degree of inconsistency among respondents. A consistency ratio equal to or below 0.10 is considered acceptable. Nevertheless, an inconsistency ratio exceeding 0.10 does not necessarily indicate an error in the AHP-based multiple criteria analysis (Saaty, 1994). If the level of consistency is unsatisfactory, the decision maker should reconsider and possibly revise the pairwise comparison judgments before proceeding with the analysis.
Development of priority ranking, the calculation of alternative ranking involves multiplying the priority vector of alternative solutions for each criterion matrix (priority matrix) by the priority vector of the criterion matrix (criteria weights). The result is the rank of the alternatives. The highest score indicated the best alternative.

The research questions were addressed using the conceptual framework illustrated in Figure 6. The Cynefin framework determines the complexity of the business issue, whereas FMEA identifies potential problems or failure modes, focusing on handling lower-ranking coal products. Risks are prioritized based on risks and prioritized based on the risk priority number, which is calculated by multiplying severity, occurrence, and detection scores. Additionally, solutions for risks or potential problems are identified and recommended using FMEA.

The Analytical Hierarchy Process (AHP) is utilized to facilitate a systematic approach for evaluating and comparing multiple criteria for the alternative solution. The VFT is used to understand and prioritize the valuable criteria for the desired outcomes. With this framework, a comprehensive assessment can be conducted to guide decision-making and identify the optimal solution. The results can be used to guide the implementation phase. By managing this process, the company can ensure that the implementation of solutions remains within the desired timeframes and financial constraints while effectively addressing the identified risks.

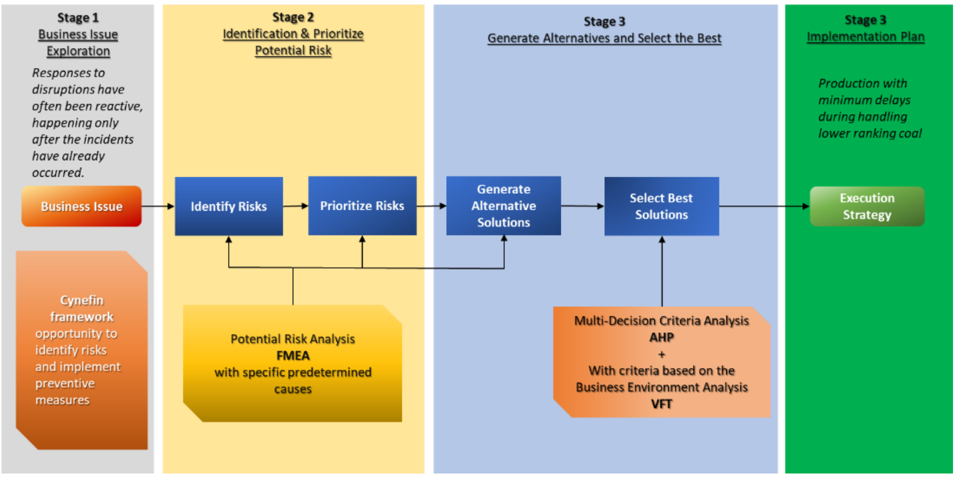

Figure 6. Conceptual Framework
Source: Author

3. Research method

3.1 Research Design

Outline the stages of the research method for this study with the following steps.

3.1.1 Business Issue Exploration

The business issue is analyzed based on the Cynefin framework to determine the complexity of the issue, whether categorized under clear/simple, complicated, complex, or chaotic. Each of the complexities comes with specific guidance outlining its characteristics, along with the recommended approach and practices for addressing the issue. The method used is a literature study on the company's internal data related to the history of events or incidents related to lower-ranking coal in the CPP area.

3.1.2 Failure Mode Effect Analysis (FMEA)

The steps involved in conducting the Failure Modes and Effects Analysis (FMEA) are as follows:

1. Identification of coal handling activities in CPP and system components for each main process. Data will be collected through direct observation and a literature review.
2. Identification of potential failure modes allows for in-depth exploration and understanding of specific risks and their correlation with lower-ranking coal activities. The analysis focused on characteristics that differ from those associated with relatively higher-ranking coal. Data collection involves a literature review and discussion with SMEs.
3. Prioritization of the risks is based on the Risk Priority Numbers (RPN) values, determined by the multiplication of Severity, Occurrence, and Non-Detection. These values were derived from the input provided by subject matter experts (SMEs). Alternatives were generated for the top three risks based on the ranking of the RPN. This determination is made through a literature review and interviews with SMEs.

3.1.3 Value Focus Thinking (VFT) and Analytical Hierarchy Process (AHP)

The results of the VFT serve as criteria for the AHP. Qualitative research methods can be beneficial for VFT analysis by enabling a thorough examination of the details and complexities of both the internal and external factors. This approach also provides the ability to explore unexpected issues and adjust parameters as required.

The pairwise comparison process was conducted by utilizing information from the questionnaire and literature review. All relevant parameters in the Analytic Hierarchy Process (AHP) will be analyzed using Super Decision AHP software. The data generated through this analysis identifies the best alternative among the options considered. The results derived from AHP serve as a foundation for the elaboration of the implementation plan.

A combination of these methodologies is depicted in the figure below. This figure illustrates how each methodology was integrated into the overall research design. The process commences sequentially, following the specified order to ensure a structured and systematic approach.

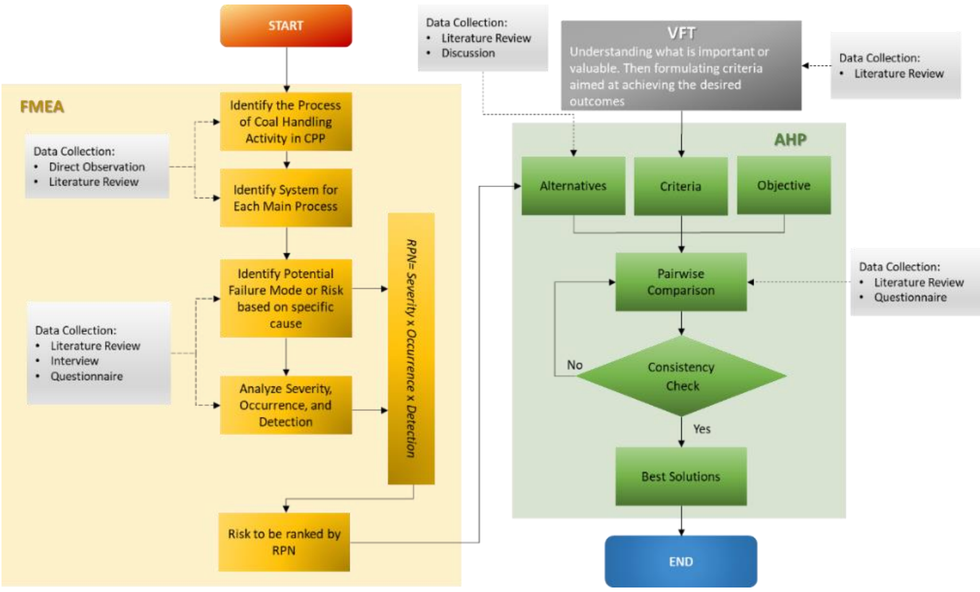

Figure 7. Research Framework
Source: Author

3.2 Data Collection Method

Sileyew (2019), primary data sourced directly from the original information, offer increased reliability and confidence in decision-making as they undergo trusted analysis directly tied to event occurrences. Secondary data collected by individuals other than users offer insights into the research area using contemporary methods. They highlight research gaps that require attention and can originate from internal or external sources covering diverse topics.

3.3 Data Analysis Method

Qualitative data were obtained through interviews and discussion. Quantitative data were obtained using questionnaire responses and analyzed using the FMEA and AHP methodologies.
Primary data will be gathered from discussions, interviews, and questionnaire surveys conducted with several respondents, as shown in Table 7. A list of stakeholders is provided with these questions. Direct observations were also used to identify the existing system.

Table 7. List of Respondents

No	Name	Role	Job Description	Years in Current Departments
1.	SME1	Manager of Coal Processing Plant Operation	Involves operating the equipment safely and as planned, leading a team, managing budgets, ensuring safety compliance, minimizing downtime, and driving continuous improvement specific on CPP area.	19
2.	SME2	Manager of Coal Processing Plant Maintenance	Ensures organizational efficiency through regular equipment maintenance the fixed plant for operational needs, safety compliance, cost-effective asset management, and continuous improvement specific on CPP area	27

No	Name	Role	Job Description	Years in Current Departments
3.	SME3	Manger of Engineer Plant Engineering & Project Services	Manage coal chain engineering and projects, ensuring they're on time, budget, and compliant. Lead teams, provide technical expertise, and oversee resources and stakeholder communication.	17
4.	SME4	Senior Project Engineer Plant Engineering & Project Services	Provide engineering & projects service related with coal chain activities	16
5.	SME5	Senior Project Engineer Plant Engineering & Project Services	Provide engineering & projects service related with coal chain activities	6

Source: Author (2024)

Secondary data for this study will be gathered from two main sources: in-house and external. In-house data include information and records that are available within the company, such as operational and maintenance (O&M) documentation, incident investigation reports, and statistical data (operational logging). External sources of data will be reviewed to complement in-house data such as journals or articles. Table 8 summarizes the data collected for each framework used.

Table 8. Data Collection Methods

Framework	Parameter	Data Collection Method	
		Primary	Secondary
FMEA	Identify Process of Coal Handling Activity	Direct observation	O&M Documentations
	Identify System for Each Main Process	Direct observation	O&M Documentations
	Identify Potential Failure Mode or Risk based on specific cause Analyse Occurrence, Detection, and Severity Recommended Action	Interview, discussion	company’s investigation reports, external journals, and articles.
VFT	Goals, criteria	Interview, discussion	external journals and articles.
AHP	Alternatives	Interview, discussion	external journals and articles.
	Pairwise Comparison	questionnaire survey	external journals and articles.

Source: Author (2024)

4. Results and discussion

2.1 Business Issue Exploration

Based on the Cynefin framework, the issue related to the handling of lower-ranking coal falls into the simple category. This is because the pattern of the issue was predictable. As stated in the company's test report by the BPPT in 2017, lower-ranking coal does not flow well without reducing its total moisture content. However, the addition of vibrations accelerates the relative flow, particularly when the vibrations occur simultaneously. This highlights the importance of considering the flowability characteristics. Additionally, the lower-ranking coal tested falls into the category of coal, which is highly reactive to spontaneous combustion.

Table 9. Characteristic of Simple Problem Based on the Cynefin Framework

Complexity	Characteristic	Approach	Practice
Clear/Simple	The connections between cause and effect are obvious, can be predicted and repeated, and typically follow a linear pattern.	sense-categorise-respond	Implement best practice

Source: Puik and Ceglarek (2015)

The pattern of fire incidents and the increasing delay in blocked chutes align with the findings of the report, emphasizing the need to address these issues. The problem tree analysis below shows the correlation between the incidents that occurred and the characteristics of the lower-ranking coal. The differing characteristics primarily contribute to the preceding incidents.

1. Higher self-combustion reactivity
2. When dry, higher ash content creates dust and airborne particles.
3. When wet, a higher ash content results in sticky material.

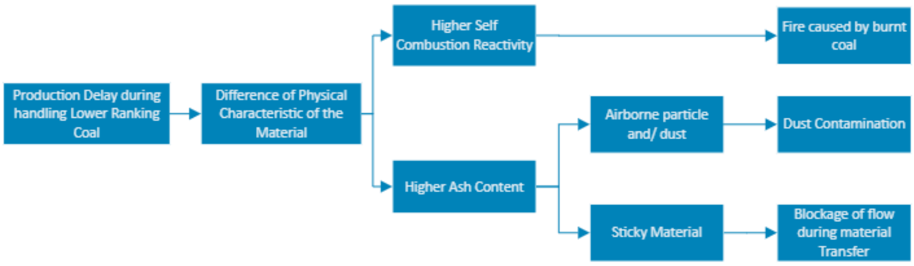

Figure 8. Problem Tree Analysis
Source: Author

2.2 Failure Mode Effect Analysis

2.2.1 Identify the Process of Coal Handling in CPP

The FMEA was developed within the scope of this study, primarily focusing on the CPP Area. The analysis addresses the main equipment system in the CPP area, specifically; Hopper: designed as a receptacle for coal delivered from mining areas via mining trucks. Feeder Breaker and Crusher: machines used to reduce the size of coal to the required product size. Chute: Structure used for transferring coal from one station to another, often from one conveyor to another. Conveyor: System comprising machinery and belts used for transporting bulk materials, including coal. Stockpile: temporary storage of materials, including coal, before they are either moved to another location or processed further. Reclaim system (tunnel): used to retrieve materials such as coal from stockpiles for transportation to other locations. The reclaimed system is located inside the tunnel.

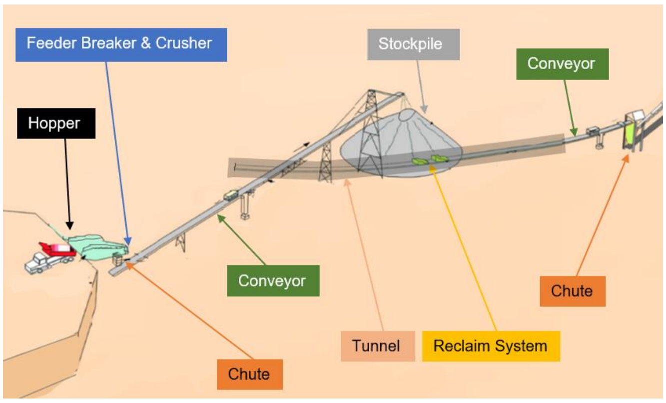

Figure 9. Simplified Coal Handling Facilities in CPP Area
Source: Internal company data (2024)

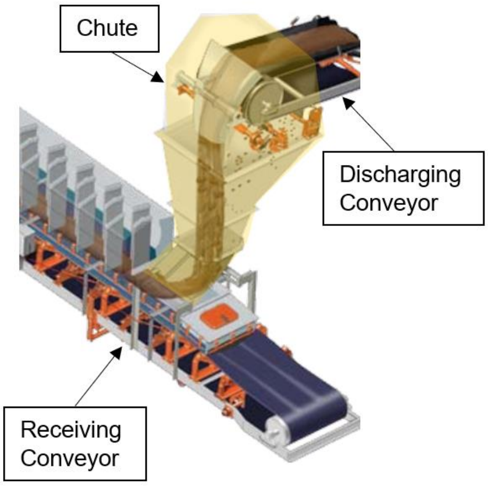

Figure 10. Illustration of Conveyor & Chute
Source: Swinderman et al.

2.2.2 Identify Potential Failure Mode or Risk Based on Specific Cause

The analysis of failure identification focused on the main system in the CPP area, as mentioned earlier. The specific cause is determined through a problem tree analysis, targeting characteristics unique to lower-ranking coal; higher self-combustion reactivity, dust/airborne particle, and ticky material.

The results of the table include identifying the subsystem, potential causes, codes, potential failure modes, potential failure effects, and potential consequences for analysis. is shown in table 10.

Table 10. FMEA Result

Sub-system	Potential Cause	Code	Potential Failure Mode	Potential Failure Effects	Potential Consequences
Hopper	fine coal/coal dust (D)	FM.HD.01	Excessive airborne coal dust	Health issue and/or safety hazard due to insufficient visibility range	Production delays or temporary stoppage due to create air pollution to the community
	Sticky Material (S)	FM.HS.01	Sticky material adhering to the chute wall	Material flow blockage, chute overfill	Production delays due to stoppage/trip the equipment
	Self-Combustion (B)	-	-	-	-
Feeder Breaker & Crusher	fine coal/coal dust (D)	FM.RD.01	Accumulation of fine coal trapped on closed space	Burning on parts/equipment	Production delays
	Sticky Material (S)	FM.RS.01	Sticky material adhering on the gaps among the tooth of the breaker or crusher	Efficiency of size reduction decreased	Decreased production rate; oversize material, potential complaint by

Sub-system	Potential Cause	Code	Potential Failure Mode	Potential Failure Effects	Potential Consequences
					customer or buyer
	Self-Combustion (B)	-	-	-	-
Chute/loading point	fine coal/coal dust (D)	FM.CD.01a	Excessive airborne coal dust through chute	Health issue and/or safety hazard due to insufficient visibility range	Production delay caused by prolonged other ongoing operational and maintenance activity
		FM.CD.01b	Excessive airborne coal dust through chute	Contamination to other equipment or sensor interference	Production delays due to stoppage/trip the equipment
		FM.CD.01c	Accumulation of fine coal trapped on closed space	Burning on parts/equipment	Production delays
	Sticky Material (S)	FM.CS.01	Sticky material adhering to the chute wall	Material flow blockage, chute overfill	Production delays due to stoppage/trip the equipment
	Self-Combustion (B)	-	-	-	-
Conveyor	fine coal/coal dust (D)	FM.VD.01	Accumulation of fine coal trapped on closed space	Burning on parts/equipment	Production delays
	Sticky Material (S)	FM.VS.01	Excessive sticky material	Excessive sticky material create lump and activate overburden sensor	Production delays due to false alarm activated.
		FM.VS.02	Sticky material difficult to be cleaned by scrapper.	Belt drift	Production delays
	Self-Combustion (B)	FM.VB.01	Burning coal burn the conveyor belt	Fire on the conveyor belt	Production delays
		FM.VB.02	Burning coal burn other parts of the conveyor	Fire on the other parts of the conveyor (cable, electrical component)	Production delays
Stockpile	fine coal/coal dust (D)	FM.PD.01a	Excessive airborne coal dust	Health issue and/or safety hazard due to	Production delay caused by prolonged other

Sub-system	Potential Cause	Code	Potential Failure Mode	Potential Failure Effects	Potential Consequences
				insufficient visibility range	ongoing operational and maintenance activity
		FM.PD.01b	Excessive airborne coal dust	Contamination to other equipment or sensor interference	Production delays due to stoppage/trip the equipment
		FM.PD.01c	Accumulation of fine coal trapped on closed space	Burning on parts/equipment	Production delays
	Sticky Material (S)	-	-	-	-
	Self-Combustion (B)	FM.PB.01a	Burning coal burn the steel structure	Coating Failure; decreased structural integrity possibility of structural collapse	Production delays
Tunnel & Reclaim System	fine coal/coal dust (D)	FM.TD.01a	coal dust spreading throughout the tunnel area	Health issue and/or safety hazard due to insufficient visibility range	Production delay caused by prolonged other ongoing operational and maintenance activity
		FM.TD.01b	coal dust spreading throughout the tunnel area	Contamination to other equipment or sensor interference	Production delays due to stoppage/trip the equipment
		FM.TD.01c	Accumulation of fine coal trapped on closed space	Burning on parts/equipment	Production delays
	Sticky Material (S)	FM.TS.01	Sticky material adhering to the drawdown hopper and chute wall	Material flow blockage, chute overfill	Production delays due to stoppage/trip the equipment
	Self-Combustion (B)	FM.TB.01a	Burning coal cause fire inside the tunnel	Fire in the tunnel	Production delays
		FM.TB.01b	Burning coal cause fire inside the tunnel	High Temperature in the Tunnel	Production delays
		FM.TB.01c	Burning coal cause fire	Poisonous gas in the Tunnel	Production delays

Sub-system	Potential Cause	Code	Potential Failure Mode	Potential Failure Effects	Potential Consequences
			inside the tunnel		

Source: Author

2.2.3 Analyse and Calculate the Risk Priority Number (RPN)

To calculate the Risk Priority Number, respondents were selected based on interviews with SMEs from operational and maintenance departments only. This is because SMEs have extensive experience in their expertise, particularly in the chosen research topic area. To maintain a focused analysis within the CPP area, respondents from engineering departments whose coverage extends beyond CPP were also intentionally excluded in this process.

The result of the interview was determined as the Risk Priority Number, calculated based on the multiplication of Severity, Occurrence, and Detection. The RPN results are presented in Table 11.

Table 11. Summary of Risk Priority Number

No	Code	SME 1				SME 2				Average Risk Priority Number	Risk Priority Number Rank
		Occurrence	Severity	Detection	RPN	Occurrence	Severity	Detection	RPN		
1	FM.HD.01	9	1	5	45	8	1	5	40	42,5	15
2	FM.HS.01	1	1	3	3	1	1	5	5	4	24
3	FM.RD.01	1	2	7	14	3	5	6	90	52	12
4	FM.RS.01	8	4	6	192	8	3	8	192	192	5
5	FM.CD.01a	9	1	1	9	9	1	3	27	18	21
6	FM.CD.01b	1	2	7	14	2	4	5	40	27	18
7	FM.CD.01c	1	4	7	28	4	4	3	48	38	17
8	FM.CS.01	10	2	7	140	9	3	9	243	191,5	6
9	FM.VD.01	2	4	7	56	3	8	6	144	100	10
10	FM.VS.01	9	2	8	144	8	2	8	128	136	7
11	FM.VS.02	9	2	8	144	9	2	7	126	135	8
12	FM.VB.01	3	10	7	210	3	9	8	216	213	4
13	FM.VB.02	3	4	7	84	1	8	7	56	70	11
14	FM.PD.01a	9	1	2	18	10	1	3	30	24	19
15	FM.PD.01b	1	2	7	14	1	3	3	9	11,5	22
16	FM.PD.01c	1	1	8	8	1	1	7	7	7,5	23
17	FM.PB.01a	9	10	2	180	1	10	7	70	125	9
18	FM.TD.01a	9	2	3	54	10	1	4	40	47	14
19	FM.TD.01b	1	3	6	18	1	4	6	24	21	20
20	**FM.TD.01c**	**4**	**6**	**7**	**168**	**6**	**7**	**7**	**294**	**231**	**2**
21	**FM.TS.01**	**9**	**6**	**6**	**324**	**8**	**8**	**7**	**448**	**386**	**1**
22	**FM.TB.01a**	**2**	**10**	**8**	**160**	**3**	**10**	**9**	**270**	**215**	**3**
23	FM.TB.01b	9	1	6	54	7	1	7	49	51,5	13
24	FM.TB.01c	8	3	3	72	2	1	6	12	42	16

Source: Author

Table 12. Involvement of Subject Matters Expert on FMEA analysis

No	Name	Role	Involvement in FMEA
1.	SME1	Manger of Coal Processing Plant Operation	Determine Risk Priority Number, input for alternatives

No	Name	Role	Involvement in FMEA
2.	SME2	Manager of Coal Processing Plant Maintenance	Determine Risk Priority Number, input for alternatives
3.	SME3	Senior Project Engineer of Engineering Dept.	Input for alternatives
4.	SME4	Senior Project Engineer of Engineering Dept.	

Source: Author

2.2.4 List of Alternatives on the Top Three Potential Failure Mode

A list of alternatives was derived from insights gathered through interviews with SMEs and a literature review. The scope covered only the top three risks. Prioritizing the top three areas is practical owing to the time constraints of the study. Additionally, it allows the company to concentrate resources effectively for thorough analysis without reducing efforts across all areas and creating a foundation for more comprehensive future studies.

Collaborative interviews with three departments–operations, maintenance, and engineering–have provided valuable perspectives, enabling the identification of effective alternatives aimed at addressing the identified failure modes. The O&M department will precisely understand what will be required as additional control based on their experience. Meanwhile, the engineering department needs an external viewpoint that can suggest alternatives or newer technology to be implemented as a solution. A literature study will also contribute to the enhancement of alternative solutions by leveraging advancements in technology that are presently not incorporated or utilized by the company.

The cost estimate for each alternative was also analyzed using internal companies and external data. The completion schedule for the alternatives was estimated using an internal data company, based on previous projects. The results of the cost estimates and schedules are presented in Table 13.

Table 13. Top Three Potential Failure Mode with List of Alternatives

Parameter	Alternative Solution	Capital Cost (IDR)	Construction Duration (week)
RPN Rank: 1 **Code:** FM.TS.01 **Sub-system:** Tunnel & Reclaim System **Potential Risk:** Sticky material adhering to the drawdown hopper and chute wall. **Potential Failure Mode:** Material flow blockage, chute overfill.	Install a booster pump on the existing water suppression system (DS) in the tunnel to increase the pressure. Pressurized water will be used to clear blockages of the sticky coal on the drawdown hopper (DDH) and chute from inside the tunnel.	375,507,792	18
	Install air cannon system in the draw-down hopper and/ transfer chute to break to the blockage coal during a significant block chute event.	916,064,364	40
	Perform a major overhaul on the existing DDH by replacing the rubber buffers, rounded rocks, liner, and outer structure. The aim is to restore the DDH to its original design (the aim is to make the flow smoother and longer vibration duration to minimize blockage).	2,734,950,636	38

Parameter	Alternative Solution	Capital Cost (IDR)	Construction Duration (week)
RPN Rank: 2 **Code:** FM.TD.01c **Sub-system:** Tunnel & Reclaim System **Potential Risk:** Accumulation of fine coal trapped on closed space. **Potential Failure Mode:** Burning on parts/equipment in the tunnel.	Periodic cleanup using a new portable blower for electrical sensitive equipment, or water for non-electrical sensitive parts.	22,104,500	10
	The cleanup process, following option above, will only be executed based on findings from daily inspections conducted using a new thermal camera.	141,124,500	11
	Reactivate dust suppression at each loading point that is currently inoperable due to broken pipes and blocked nozzles. Activation will be based on visual surveillance of the dust at each stockpile, facilitated by the installation of new CCTV (Closed Circuit Television) cameras monitored by the control room operator.	281,223,800	27
RPN Rank: 3 **Code:** FM.TB.01a **Sub-system:** Tunnel & Reclaim System **Potential Risk:** Burning coal cause fire inside the tunnel. **Potential Failure Mode:** Burning on parts/equipment in the tunnel.	Install CCTV coverage throughout the entire length of the tunnel and implement smoke detector monitoring. Each time a smoke detector is activated, it can be verified through CCTV whether it is caused by a fire inside the tunnel or by smoky coal.	179,124,244	14
	Install thermal cameras or imaging devices to cover the entire length of the tunnel. This includes an early warning system based on algorithms derived from thermal imaging.	1,171,638,710	18
	Install additional temperature monitoring at each loading point, which integrates with conveyor stopping status. If high temperature is detected at a certain loading point and the conveyor subsequently stops within a specific timeframe, indicating that hot material remains on the belt, an alarm will be activated to ensure an actual check in the field will be performed by operator.	96,097,760	19

Source: Author

2.3 Value Focus Thinking

The hierarchy of the VFT is illustrated in Figure 10. The average objectives are then used as criteria in the AHP, which include; Effectiveness: Precision is employed in problem-solving methodologies to achieve optimal outcomes. Financial Aspects: Comparison of required capital costs. Operability and Maintainability: Ease of operational activities and maintenance. Procurement and Construction

Duration: The duration from the acquisition process until new equipment or process can be implemented.

2.4 Analytical Hierarchy Process

The alternatives for the top three ranks from the FMEA are analyzed through AHP. The values for comparison in AHP are gathered from structured interviews, which include subject matter experts (SMEs). To conduct pairwise comparisons, respondents were selected from the managers of three departments closely associated with the operational aspects of a fixed plant in the CPP area: Operational, Maintenance and Engineering. The inclusion of managers as respondents was justified because of their technical expertise and direct involvement in cost management. This provides insights into both technical and cost concerns.

2.4.1 Construct Structure a Hierarchy

The hierarchical structure is then classified for each of the top three risks, that is, (1) *FM.TS.01:* sticky material adhering to the drawdown hopper and chute wall, (2) *FM.TD.01c*: accumulation of fine coal trapped in closed space, and (3) *FM.TB.01a:* burning coal causes fire inside the tunnel. This classification also involves identifying three leading alternatives, as outlined in Table 12. The criteria were determined from the mean objectives of the value-focused thinking process.

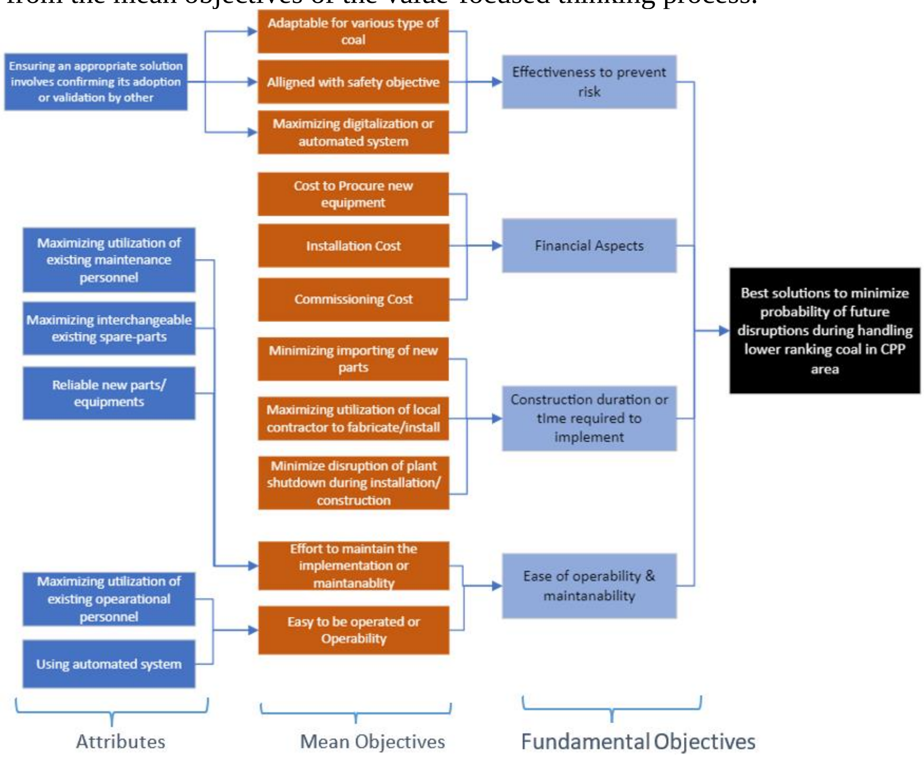

Figure 10. Hierarchy of Value Focus Thinking
Source: Author

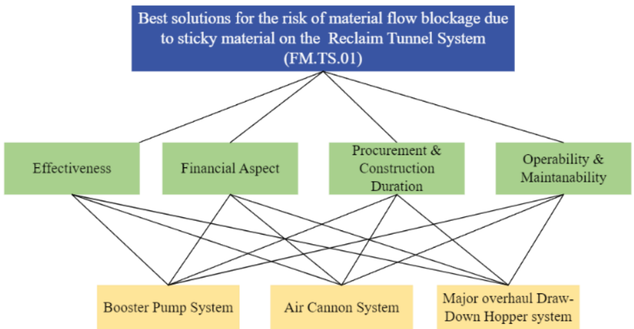

Figure 11. Hierarchy of AHP Model for Failure Mode FM.TS.01
Source: Author

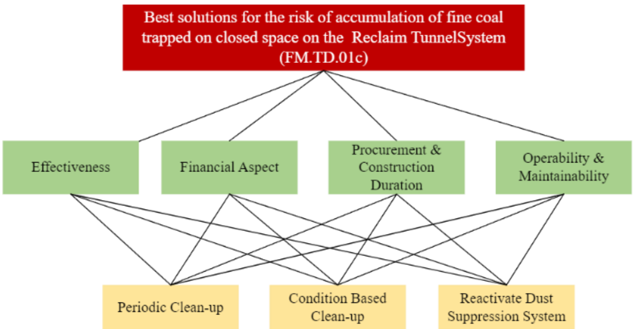

Figure 12. Hierarchy of AHP Model for Failure Mode FM.TD.01c
Source: Author

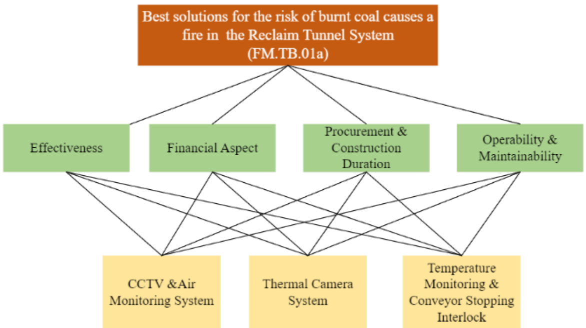

Figure 13. Hierarchy of AHP Model for Failure Mode FM.TB.01a
Source: Author

2.4.2 Pairwise Comparison of AHP-Model

The criteria and alternative options were translated into survey format through pairwise comparisons. The respondents were requested to provide ratings for each comparison table using a fundamental value scale, as shown in Table 6.

For pairwise comparisons, respondents were required to provide assessments for all four criteria: effectiveness, financial aspects, procurement-construction duration, operability, and maintainability. However, for pairwise comparisons of alternatives, respondents only needed to evaluate two criteria: effectiveness, operability, and maintainability. The author will make a compares the financial aspect values and construction duration for each alternative. This is essential to ensure objectivity, as financial aspects and construction duration values must be consistently compared during the AHP process. If assessed by SMEs, the values may differ, as this is not within the expertise of the SME and requires reference from the literature. The results for the financial aspect and construction duration are presented in Table 13. The Pairwise questionnaire for the criteria is presented in Tables 14, 15, and 16.

For the computations in this final project, the geometric mean derived from pairwise comparisons among all SMEs was used. The results of the pairwise comparison of the criteria are presented in Table 16. The pairwise comparisons of alternatives are presented in Tables 17, 18, and 19.

Table 14. Pairwise questionnaire of criteria

Question:
Which of the following criteria do you think is more important for choosing the best alternatives as additional control related to risk in CPP#1 Tunnel Reclaim system during handling lower-ranking coa for each risk beow:
1. Best solutions for the risk of material flow blockage due to sticky material on the Reclaim Tunnel System (FM.TS.01)
2. Best solutions for the risk of accumulation of fine coal trapped on closed space on the Reclaim Tunnel System (FM.TD.01c)
3. Best solutions for the risk of burnt coal causes a fire in the Reclaim Tunnel System (FM.TB.01a)

Criteria	Pairwise Numerical Rating																	Criteria
Effectiveness	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Economic Evaluation
Effectiveness	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Operability & Maintainability
Effectiveness	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Construction Duration
Financial Aspect	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Operability & Maintainability
Financial Aspect	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Procurement & Construction Duration
Operability & Maintainability	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Procurement & Construction Duration

Source: Author

Table 15. Pairwise questionnaire of alternative solutions for FM.TS.01

Based on criteria: ***Effectiveness; Financial Aspect; Operability & Maintainability; Procurement & Construction Duration,*** which one of the following alternatives do you think is more prefferable for the best solutions for the risk of material flow blockage due to sticky material on the Reclaim Tunnel System (FM.TS.01)

Alternatives	Pairwise Numerical Rating																	Alternatives
Booster Pump System	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Air Cannon System
Booster Pump System	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Overhaul Draw-Down Hopper system
Air Cannon System	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Overhaul Draw-Down Hopper system

Source: Author

Table 16. Pairwise questionnaire of alternative solutions for FM.TD.01c

Based on criteria: ***Effectiveness; Financial Aspect; Operability & Maintainability; Procurement & Construction Duration,*** which one of the following alternatives do you think is more prefferable for the best solutions for the risk of accumulation of fine coal trapped on closed space on the Reclaim TunnelSystem (FM.TD.01c)

Alternatives	Pairwise Numerical Rating																	Alternatives
Periodic clean-up	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Condition based clean-up
Periodic clean-up	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Reactivate Dust Supression System
Condition based clean-up	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Reactivate Dust Supression System

Source: Author

Table 17. Result of pairwise comparison of criteria

No	Pairwise comparison of Criteria	Respondents			Geometric Mean
		SME1	SME2	SME3	
1.	Effectiveness - Financial Aspect	7.00	7.00	9.00	7.67
2.	Effectiveness - Operability & Maintainability	5.00	0.11	1.00	0.82
3.	Effectiveness - Procurement & Construction Duration	9.00	1.00	1.00	2.08
4.	Financial Aspect - Operability & Maintainability	0.25	0.11	0.17	0.17
5.	Financial Aspect - Procurement & Construction Duration	3.00	1.00	0.17	0.79
6.	Operability & Maintainability - Procurement & Construction Duration	7.00	9 .00	0.33	1.51

Source: Author

Table 18. Pairwise Comparison Results for Failure Mode FM.TS.01

No	Criteria	Pairwise comparison of alternatives	Respondents			Geometric Mean
			SME1	SME2	SME3	
1.	Effectiveness	Booster Pump System - Air Cannon System	0.17	1.89	1.89	1.89

No	Criteria	Pairwise comparison of alternatives	Respondents			Geometric Mean
			SME1	SME2	SME3	
		Booster Pump System - Overhaul Draw-Down Hopper System	4.00	5.76	5.76	5.76
		Air Cannon system - Overhaul Draw-Down Hopper System	9.00	3.00	3.00	3.00
2.	Financial Aspect	Booster Pump System - Air Cannon System				2,44
		Booster Pump System - Overhaul Draw-Down Hopper System	Based on data estimation and calculation on table 13			7,28
		Air Cannon system - Overhaul Draw-Down Hopper System				2,99
3.	Operability & Maintainability	Booster Pump System - Air Cannon System	7.00	3.97	3.97	3.97
		Booster Pump System - Overhaul Draw-Down Hopper System	0.33	0.83	0.83	0.83
		Air Cannon system - Overhaul Draw-Down Hopper System	0.11	0.30	0.30	0.30
4.	Procurement & Construction Duration	Booster Pump System - Air Cannon System				2,22
		Booster Pump System - Overhaul Draw-Down Hopper System	Based on data estimation and calculation on table 13			2,11
		Air Cannon system - Overhaul Draw-Down Hopper System				0,95

Source: Author

Table 19. Pairwise Comparison Results for Failure Mode FM.TD.01c

No	Criteria	Pairwise comparison of alternatives	Respondents			Geometric Mean
			SME1	SME2	SME3	
1.	Effectiveness	Periodic clean-up - Condition based clean-up	0.13	3.38	7.00	2.11
		Periodic clean-up – Reactivate Dust Suppression System	5.00	2.06	7.00	4.08
		Condition based clean-up - Reactivate Dust Suppression System	9.00	0.91	0.50	3.22
2.	Financial Aspect	Periodic clean-up - Condition based clean-up				6.38
		Periodic clean-up – Reactivate Dust Suppression System	Based on data estimation and calculation on table 13			9.00
		Condition based clean-up - Reactivate Dust Suppression System				1.99
3.	Operability & Maintainability	Periodic clean-up - Condition based clean-up	1.00	0.79	0.5	0.83
		Periodic clean-up – Reactivate Dust Suppression System	6.00	1.84	8.00	4.71

No	Criteria	Pairwise comparison of alternatives	Respondents			Geometric Mean
			SME1	SME2	SME3	
		Condition based clean-up - Reactivate Dust Suppression System	6.00	1.83	6.00	4.06
4.	Procurement & Construction Duration	Periodic clean-up - Condition based clean-up	Based on data estimation and calculation on table 13			1.20
		Periodic clean-up – Reactivate Dust Suppression System				2.70
		Condition based clean-up - Reactivate Dust Suppression System				2.25

Source: Author

Table 20. Pairwise Comparison Results for Failure Mode FM.TB.01a

No	Criteria	Pairwise comparison of alternatives	Respondents			Geometric Mean
			SME1	SME2	SME3	
1.	Effectiveness	CCTV& air monitoring system - Thermal Camera System	0.25	0.30	0.30	0.30
		CCTV& air monitoring system - Temperature monitoring & conveyor stopping interlock	6.00	1.59	1.59	1.59
		Thermal Camera System - Temperature monitoring & conveyor stopping interlock	9.00	2.75	2.75	2.75
2.	Financial Aspect	CCTV& air monitoring system - Thermal Camera System	Based on data estimation and calculation on table 13			6.54
		CCTV& air monitoring system - Temperature monitoring & conveyor stopping interlock				0.54
		Thermal Camera System - Temperature monitoring & conveyor stopping interlock				0.08
3.	Operability & Maintainability	CCTV& air monitoring system - Thermal Camera System	1.00	0.55	0.55	0.55
		CCTV& air monitoring system - Temperature monitoring & conveyor stopping interlock	0.11	0.38	0.38	0.38
		Thermal Camera System - Temperature monitoring & conveyor stopping interlock	0.11	0.87	0.87	0.87
4.	Procurement & Construction Duration	CCTV& air monitoring system - Thermal Camera System	Based on data estimation and calculation on table 13			1.29
		CCTV& air monitoring system - Temperature monitoring & conveyor stopping interlock				1.36
		Thermal Camera System - Temperature monitoring & conveyor stopping interlock				1.06

Source: Author

2.4.3 Synthesize the Results to Determine the Optimal Alternative Solution

The mean results of the pairwise comparisons were then synthesized. This applies to the matrix criteria and pairwise comparisons for all alternatives. The results are presented in tables 21-24.

Table 21. Pairwise comparison of matrix criteria

Criteria	Effectiveness	Financial Aspect	Operability & Maintainability	Procurement & Construction Duration
Effectiveness	1.00	7.67	0.82	2.08
Financial Aspect	0.13	1.00	0.17	0.79
Operability & Maintainability	1.21	5.88	1.00	1.51
Procurement & Construction Duration	0.35	1.26	0.66	1.00

Source: Author

Table 22. Pairwise comparison of alternatives for Failure Mode FM.TS.01

Criteria: Effectiveness			
Alternatives	**Booster Pump system**	**Air Cannon system**	**New Draw-Down Hopper system**
Booster Pump system	1.00	1.89	5.76
Air Cannon system	0.52	1.00	3.00
New Draw-Down Hopper system	0.17	0.33	1.00
Alternatives	**Booster Pump system**	**Air Cannon system**	**New Draw-Down Hopper system**
Booster Pump system	1.00	2.44	7.28
Air Cannon system	0.41	1.00	2.99
New Draw-Down Hopper system	0.14	0.33	1.00
Alternatives	**Booster Pump system**	**Air Cannon system**	**New Draw-Down Hopper system**
Booster Pump system	1.00	3.97	0.83
Air Cannon system	0.25	1.00	0.30
New Draw-Down Hopper system	1.20	3.33	1.00
Alternatives	**Booster Pump system**	**Air Cannon system**	**New Draw-Down Hopper system**
Booster Pump system	1.00	2.22	2.11
Air Cannon system	0.45	1.00	0.95
New Draw-Down Hopper system	0.47	1.05	1.00

Source: Author

Table 23. Pairwise comparison of alternatives for Failure Mode FM.TD.01c

Criteria: Effectiveness			
Alternatives	**Periodic clean-up**	**Condition based clean-up**	**Auto chemical suppression**
Periodic clean-up	1.00	3.44	4.08
Condition based clean-up	0.29	1.00	3.22
Auto chemical suppression	0.25	0.31	1.00
SCriteria: Financial Aspect			
Alternatives	**Periodic clean-up**	**Condition based clean-up**	**Auto chemical suppressi on**
Periodic clean-up	1.00	6.38	9.00

Condition based clean-up	0.16	1.00	1.99
Auto chemical suppression	0.11	0.50	1.00
Criteria: Operability & Maintainability			
Alternatives	**Periodic clean-up**	**Condition based clean-up**	**Auto chemical suppression**
Periodic clean-up	1.00	0.83	4.71
Condition based clean-up	1.2	1.00	4.06
Auto chemical suppression	0.21	0.25	1.00
Criteria: Procurement & Construction Duration			
Alternatives	**Periodic clean-up**	**Condition based clean-up**	**Auto chemical suppression**
Periodic clean-up	1.00	1.20	2.70
Condition based clean-up	0.83	1.00	2.25
Auto chemical suppression	0.37	0.44	1.00

Source: Author

5. Conclusion

The results of this study will provide an understanding of the identification of risks and determination of optimal solutions for the handling of lower-ranking coal within the CPP area. The results answer the research questions provided in the previous section as follows. Excessive airborne coal dust causes health issues or safety hazards owing to the insufficient visibility range. The sticky material adhering to the chute wall causes material flow blockage and chute overfill. The accumulation of fine coal trapped in closed spaces causes burning of parts equipment. Sticky material adhering to the gaps between the teeth of the breaker or crusher causes the efficiency of size reduction to decrease.

The nexts is conveying, from that research the author mentions that excessive airborne coal dust through a chute can cause health issues and/or safety hazards owing to insufficient visibility range and contamination with other equipment or sensor interference. Excessive sticky materials create lumps and activate the overburden sensors. The sticky material adhering to the chute wall causes material flow blockage and chute overfill. The accumulation of fine coal trapped in closed spaces causes burning of parts/equipment. Sticky material that is difficult to clean using scrappers causes belt drift. Burning coal burns the conveyor belt, causing fire on the conveyor belt or on other parts of the conveyor (cable and electrical component).

The stockpile are excessive airborne coal dust causes health issues and/or safety hazards owing to the insufficient visibility range. Excessive airborne coal dust can cause contamination by other equipment or sensor interference. The accumulation of fine coal trapped in closed spaces causes burning of parts/equipment. Burning coal burns the steel structure, causing coating failure and decreasing the possibility of structural collapse.

Limitations and study forward

The limitations of this research are the system subjected to Failure Mode Effect Analysis (FMEA) analysis is not an in-depth breakdown into sub-systems or detailed component levels of the equipment. The alternative recommendation was derived from collaborative brainstorming sessions with subject matter experts within the company. The alternative recommendation will consist of general guidance, necessitating further elaboration. To explore the alternatives, collaborating with industry experts or conducting benchmarking to other companies can gain insights beyond the results identified in this research.

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