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Improving Productivity and Operational Efficiency in Overburden Removal at a Nickel Mine Using a Lean Six Sigma Integration Approach

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ABSTRACT

The increasing global demand for nickel, driven by the rapid expansion of electric vehicle battery production and the clean energy transition, has intensified the need for highly efficient mining operations. Overburden removal represents a critical stage in nickel mining because its productivity directly affects ore extraction continuity and overall operational performance. However, PT X, a nickel mining contractor in Southeast Sulawesi, has consistently failed to achieve its overburden productivity target of 280 BCM/hour, resulting in increased operational costs and substantial financial losses. This study aimed to improve productivity and operational efficiency in overburden removal by integrating the Lean Six Sigma approach with the DMAIC framework, Failure Mode and Effects Analysis (FMEA), and Fault Tree Analysis (FTA). A mixed-method case study approach was employed using operational data collected from January 2024 to July 2025, supplemented by field observations and Focus Group Discussions (FGDs). The findings showed that 51.4% of total productivity losses were attributed to controllable delays. FMEA identified Repair Front (RPN = 400), Repair Disposal/Dumping Point (RPN = 200), and Road Maintenance (RPN = 144) as the highest-priority risks, while FTA traced these failures to deficiencies in operational supervision, equipment availability, quarry material supply, and geotechnical conditions. Improvement strategies developed through FGDs included optimizing equipment allocation, strengthening preventive maintenance practices, improving drainage systems, enhancing supervisory procedures, and reinforcing cross-functional coordination. Economic evaluation indicated that the proposed mitigation strategies were feasible, producing a Benefit-Cost Ratio (BCR) of 1.53. The integration of Lean Six Sigma, FMEA, and FTA provided a systematic and sustainable framework for reducing operational waste, minimizing process variation, and improving productivity in nickel mining operations.

INTRODUCTION

Nickel is one of the strategic mining commodities whose role has become increasingly important in the global economy. In addition to being widely used in various manufacturing products, including household appliances, electronic devices, and coating materials, nickel has become a key component in the production of high-capacity batteries for electric vehicles. As the global transition toward clean energy and electric mobility accelerates, worldwide demand for nickel continues to increase significantly. In this context, Indonesia, as the country with the largest nickel reserves globally, occupies a strategic position within the international supply chain. This condition provides substantial opportunities not only to increase the mining sector's contribution to national revenue but also to promote operational efficiency and enhance the competitiveness of the national mining industry in a sustainable manner.

At the operational level, the success of nickel ore production is highly dependent on the efficiency and continuity of mining processes, particularly during the initial stage of overburden stripping. This process is critical because it directly influences the sustainability of ore extraction activities and the achievement of production targets. PT X, a nickel mining contractor operating in Southeast Sulawesi, considers overburden stripping one of its main operational processes. However, its implementation continues to face various operational challenges that negatively affect productivity performance.

Based on the company's operational reports for the 2024–2025 period, overburden stripping productivity has not achieved the established target of 280 BCM/hour. Actual performance data indicate that the average productivity reached only 235 BCM/hour in 2024 and 225 BCM/hour until July 2025. The gap between the target and actual achievement has directly contributed to increased operational costs and potential financial losses amounting to IDR 34,830,507,625.50. These findings indicate a significant operational problem requiring a systematic and integrated improvement approach.

Furthermore, delays in overburden stripping activities not only reduce productivity within the stripping process but may also create a domino effect throughout the overall mining operation. Delays in overburden stripping can hinder the readiness of the ore mining front, disrupt the continuity of ore getting activities, and affect production planning and control in subsequent stages. This condition reduces operational stability and makes production performance more difficult to predict. Recurrent performance instability increases the risk of failing to achieve production targets, complicates daily operational control, and encourages reactive decision-making rather than preventive management Hakim et al. (2026) (Susanti, 2012).

In general, variations in overburden stripping productivity are influenced not only by technical factors within the operational cycle but also by various supporting factors affecting process stability and continuity. External factors beyond operational control, such as weather conditions, may contribute to disruptions, while internal factors that remain manageable may generate waste and performance variations if they are not systematically controlled. The accumulation of these disruptions and inefficiencies extends operating cycle times, reduces process efficiency, and contributes to unstable productivity achievement.

The recurring and uncontrolled variations in process performance indicate that the challenges faced are not isolated incidents but rather systemic problems within mining operations. This condition requires a structured, systematic, and data-driven improvement approach to identify dominant sources of variation and operational waste. Therefore, an integrated method is needed to combine waste reduction efforts with process variation control in order to achieve sustainable operational improvements.

Within the operational context of nickel mining, process variation and waste are particularly evident in overburden stripping activities. The overburden removal process consists of interconnected and repetitive activities, including loading, hauling, and dumping stages, where disruption or delay at one stage may directly affect the overall performance of the stripping system. Each operational stage has the potential to generate delays that contribute to cycle-time variation and reduced productivity.

The overburden stripping process in nickel mining consists of loading, hauling, and dumping stages, each of which has the potential to create delays that reduce operational productivity (Setiyaningrum et al., 2019; Tubagus Ismail & Yudoko, 2025; Yanuar Rahmat Syah et al., 2021). At the loading stage, delays are generally associated with imbalance in the number of hauling units, coordination delays with supporting teams, and variations in operator performance. During the hauling stage, delays may result from unfavorable road conditions, reduced equipment speed, and heavy equipment congestion. Meanwhile, delays during the dumping stage may occur due to disposal area queues, limited disposal capacity, and suboptimal material spreading activities. These conditions indicate the presence of non-value-added activities (waste) and process variations that contribute to the failure to achieve overburden stripping productivity targets. Although PT X has implemented a Six Sigma-based improvement program using the DMAIC methodology to reduce process variation and improve operational quality (Bhargava & Gaur, 2021; Mittal et al., 2023), this approach remains limited in identifying waste sources and optimizing overall process flow.

Alternatively, the Lean Management approach is considered effective in identifying and eliminating non-value-added activities, improving value-stream flow, and enhancing operational efficiency (Singh, 2015; Wang, 2010). However, Lean has limitations in statistically analyzing process variation. Therefore, previous studies have recommended integrating Lean and Six Sigma through the Lean Six Sigma approach (Drohomeretski et al., 2014 ; Salah et al., 2010). This integrated methodology combines Lean's capability to eliminate waste with Six Sigma's ability to control process variation, resulting in improved productivity, reduced operational costs, and enhanced process quality (Kadarova & Demecko, 2016; Setijono et al., 2012; Lee & Chang, 2010). Previous research has demonstrated that Lean Six Sigma has been successfully applied across various industrial sectors, including manufacturing, services, and mining (Citybabu & Yamini, 2023; Gupta et al., 2020; Hia et al., 2024; Kaswan et al., 2023; Kumar Mishra et al., 2025; Mohd Zamri et al., 2013; Nyata & Wiguna, 2018; Raja Sreedharan & Raju, 2016).

Based on these conditions, this study aimed to apply a Lean Six Sigma approach based on the DMAIC framework to improve productivity and operational efficiency in overburden stripping activities at a nickel mine. The analysis integrated Failure Mode and Effects Analysis (FMEA) to identify and prioritize potential process failures and Fault Tree Analysis (FTA) to determine the root causes of productivity decline. The research focused on the overburden stripping process at PT X, Southeast Sulawesi, using operational data collected from January 2024 to July 2025, with emphasis on controllable delays and productivity performance. The results were expected to provide measurable and sustainable improvement recommendations for the company while contributing to the development of Lean Six Sigma applications in the mining industry, particularly in improving productivity, operational efficiency, and risk management.

METHOD

Types of Research

This research was an applied study using a mixed-method approach with a case study design focusing on the overburden stripping process at PT X's nickel mine in Southeast Sulawesi. The quantitative approach was used to analyze productivity performance, delays, and process failure risks through the application of Lean Six Sigma based on the DMAIC framework, incorporating Failure Mode and Effects Analysis (FMEA) for risk assessment and Fault Tree Analysis (FTA) for root cause identification. Meanwhile, the qualitative approach was employed to enrich the analysis through field observations and Focus Group Discussions (FGDs) with relevant practitioners to formulate practical and applicable improvement strategies. Thus, this research adopted a descriptive-analytical and problem-solving-oriented approach aimed at developing systematic, data-driven recommendations to improve productivity and operational efficiency.

Data Collection

Data collection in this study was carried out using primary data and secondary data obtained from PT X's nickel mining operational activities in Southeast Sulawesi.

1. Secondary data includes Overburden stripping productivity data, *Delay* productivity records, daily operating reports, and other supporting data collected in the period January 2024 to July 31, 2025.
2. Meanwhile, primary data is obtained through field observation and discussions with related parties, such as operational supervisors, heavy equipment operators, and project management teams, to validate actual conditions and identify potential wastes and risk of process failure. The collected data is then used as the basis for *DMAIC-based* Lean Six Sigma analysis, specifically for *Waste* identification, risk assessment using FMEA, and root cause tracing through *Fault Tree Analysis* (FTA).
3. The FGD was held in a structured manner to formulate *a Lean Six Sigma-based* improvement strategy, involving key practitioners consisting of operational supervisors, mine engineers, dispatchers. The results of the FGD are used to agree on priority risks, trace the root causes, and formulate realistic and applicable improvement recommendations.

All data collected were then analyzed using *a Lean Six Sigma* approach based on the DMAIC framework, with FMEA used for the assessment of dominant risks and FTA for deepening the root cause of failure.

RESULTS AND DISCUSSION

Process Efficiency using the LEAN- SIX SIGMA Approach

The Overburden Removal process in nickel mines is an important activity that affects the smooth running of mining operations (Alvarizzy et al., 2024; Oggeri et al., 2019). This process includes loading materials, transporting them to the disposal area, dumping, and returning the unit to the loading area. In its implementation, this process often experiences inefficiencies, such as tool waiting times, dump truck queues, fleet imbalances, suboptimal hauling road conditions, heavy equipment breakdowns, and weak coordination between work areas (Djenadic et al., 2019; Odeyar et al., 2022).

To analyze and improve the efficiency of the process, this study uses *the Lean Six Sigma* approach with the DMAIC method (Bicheno & Holweg, 2016). The *Define stage* is carried out through the identification of the Overburden Removal process. The *Measure* stage is carried out by classifying activities into VA, NVA, and NNVA and identifying waste. The *Analyze* stage is carried out using FMEA to determine priority risks and FTA to trace the root cause. Furthermore, the *Improve* stage is used to develop improvement strategies, while *the Control* *stage* is designed to maintain the sustainability of improvement through performance indicators, SOPs, and monitoring mechanisms.

Thus, DMAIC is used as the main framework to connect the process of problem identification, waste measurement, risk analysis, root cause tracing, improvement preparation, and process control systematically.

1. **DEFINE: Identify the *Overburden Removal Process***

The first stage in the *Lean Six Sigma* approach is *Define*. This stage aims to determine the scope of the problem and formulate the objectives of the project to be implemented. In the context of nickel mining, the overburden removal process is a crucial stage that plays an important role in supporting the smooth operation of mining operations.

This process is often faced with various challenges, one of which is the occurrence of delays that can hinder the running of operations and have an impact on reducing hourly productivity. This condition can certainly be detrimental to the Company if not handled properly, after observations were made from data taken from January 2024 to July 2025 there were 8 *controllable delays* that occurred at the PT. X is:

a. Repair Front
b. Long retreat front maneuvers
c. Narrow Front
d. Repair Disposal / Dumping Point
e. Road Maintenance
f. Disposal/Dumping Point Crowded
g. Front Crowded
h. Crowded Street

2. **MEASURE: Identify VA, NVA, NNVA, and Waste in the Overburden Removal Process**

The second stage in *the Lean Six Sigma* approach is *Measure*. This stage aims to measure the performance of the ongoing process and collect relevant data related to delays in *overburden removal activities*. Measurements are carried out to obtain an actual picture of operational conditions, including the frequency, duration, and type of *delay* that occurs. The data obtained at this stage is the basis for identifying problem patterns and determining priority for improvement at the next stage.

The data used in *the Measure stage* is obtained through two main sources. First, secondary data is in the form of an annual production report which includes a recapitulation of the type of delay, duration, frequency of events, and *loss productivity* in BCM units. This data is used to obtain a quantitative picture of operational performance during the observation period. Second, primary data obtained through direct observation in the field to validate the actual operational conditions of *Overburden Removal*, including the condition of the mining front, hauling route, and disposal area. The combination of these two data sources allows for a comprehensive and objective picture of the *delay* patterns that occur, so that it can be a valid basis for determining improvement priorities at the next stage of analysis.

Table 1. Data Loss Productivity, Duration, and Frequency of Delay of Overburden Removal Activities

Delay Type	Loss Productivity (BCM)	Duration (Hours/Year)	Frequency (Number of Events per Year)
Repair Front	152.088,00	542,88	1207
Long Recoil Front Maneuvers	8.955,00	31,98	59
Narrow Front	3.373,00	11,56	22
Repair Disposal / Dumping Point	107.589,00	384,25	328
Road Maintanance	24.409,00	87,18	436
Dumping Point Crowded	59.663,00	275,45	165
Crowded Street	12.538,00	374,87	150
Front Crowded	32.082,00	350,21	298

Based on the data collected, the contribution of *productivity loss* shows an uneven distribution, where most of the productivity loss is concentrated on some specific type of *delay*. In addition, the difference between the frequency of occurrence and duration per occurrence indicates a variation in the characteristics of delay, reflecting differences in operational patterns as well as potential underlying causes.

Table 2. Identity OR, NVA, NNAV

Activities	Category	Remarks
Digging & loading	VA	Directly results in overburden shifting
Transportation of materials to disposal	VA	Directly contributes to the removal of overburden
Dumping material di disposal point	VA	Is the final output of the production cycle
Tool maneuver (far recoil front)	NVA	Maneuver time that does not result in production should be reduced through more effective work area arrangements.
Road Maintenance	NNVA	It is not directly productive but is necessary to maintain smooth running
Repair Front	NNVA	Work area repair activities that do not result in direct production, but are necessary to support smooth operations.
Repair Disposal / Dumping Point	NNVA	Disposal area repair activities that do not result in direct production, but are needed to support the sustainability of operations.
Narrow Front	NVA	Pure downtime, it should be reduced
Dumping Point Crowded	NVA	Pure waiting time due to queues, should be reduced
Crowded Street	NVA	Purely waiting time due to the traffic density of the equipment, should be reduced.
Front Crowded	NVA	Purely waiting time due to the density of the work area, should be reduced.

From the results of the classification above, it was identified that most of the delays that occurred were included in the NNVA (*Non Value Added Activity*) category, especially repair *front* and *repair disposal* which cumulatively contributed the largest loss of productivity This condition shows that there is significant waste in the form of downtime and waiting which is the top priority to be eliminated.

These findings suggest that not all types of *Delay* have an equal degree of influence on production performance. Therefore, further analysis is needed to identify the root cause of the most dominant Delay. In the next stage, the analysis is carried out using *the Failure mode and Effect Analysis (FMEA)* method to determine the priority of handling based on the level of risk posed by each *Delay*.

3. ANALYZE (1): Risk Analysis using FMEA

At this stage, the prioritization process is carried out on the type of delay using *the Failure mode and Effect Analysis* (FMEA) method and continues with the search for the root of the problem using *Fault Tree Analysis* (Huang et al., 2020; Kabir, 2017; Liu et al., 2019; Peeters et al., 2018; Wessiani & Yoshio, 2018; Whiteley et al., 2016; Zheng & Tang, 2020).

Table 3. Identification of Failure Modes

Process	Failure Mode
Loading	Repair Front
Loading	Long Recoil Front Maneuvers
Loading	Narrow Front
Hauling	Road Maintanance
Dumping	Repair Disposal / Dumping Point
Dumping	Dumping Point Crowded
Hauling	Crowded Street
Loading	Front Crowded

The identification process is carried out based on operational data and observations of activities in the field, especially those related to delays that often occur during the observation period. Each *identified failure mode* represents a specific condition or problem that causes the disruption of normal workflow at each stage of the process.

In the loading process, several *failure modes* were identified such as *repair front*, non-optimal tool maneuvers (long backward front maneuvers), and narrow front conditions. These problems show that there are obstacles in the readiness of the work area and the interaction between the excavation and the transport equipment, which has the potential to cause delays in the loading process.

In the *hauling process*, the *failure mode* identified is *road maintenance*, which reflects the condition of the transportation road that is not optimal in supporting smooth operations. This condition has the potential to cause obstacles in the movement of transportation equipment and trigger delays during the material transportation process.

Meanwhile, in the dumping process, the *failure mode* identified is *the* crowded *dumping point* condition. This shows that there is an imbalance between the capacity of the *disposal* area and the number of operating equipment, so it has the potential to cause queues and delays in the material disposal process.

By identifying *failure modes* at each stage of the process, an initial overview of the main sources of *delay* in mining activities can be obtained. This identification is an important basis for further analysis, especially in evaluating the impact and determining priorities for addressing the problems that have the greatest impact on productivity declines.

Table 4. Impact Identification

Failure Mode	Effect
Repair Front	Loading is stopped so that the actual productivity drops from the target
Long Recoil Front Maneuvers	Cycle time increases so that the hauler ritase decreases
Narrow Front	The hauler maneuver area is limited so that idle time increases
Road Maintanance	Poor road conditions cause the hauler speed to decrease
Repair Disposal / Dumping Point	Waiting time increases so that rritis is reduced
Dumping Point Crowded	Waiting time increases so that rritis is reduced
Crowded Street	Road conditions that are too congested cause the hauler speed to decrease
Front Crowded	The hauler maneuver area is limited so that idle time increases

After identifying *failure modes* at each stage of the mining process, the next step is to identify the effects caused by each of these *failure modes*. This impact identification aims to understand the operational consequences that occur, especially those related to increased delays and decreased equipment productivity.

Every *failure mode* that occurs affects operational performance in the form of disruption of the tool's work cycle, either through the cessation of activities, increased waiting time, or increased cycle *time*. These impacts will ultimately contribute to a reduction in effective working hours and a decrease in the amount of production that can be achieved in a given period.

In the *loading process*, *failure modes* such as *repair front* cause loading activities to be temporarily stopped, thereby reducing the effective working time of the excavation and loading tool. This impact directly lowers actual productivity compared to the planned target. In addition, the suboptimal maneuvering conditions of the tool and the narrow front cause limited tool movement space, which has an impact on increasing maneuver time and extending *cycle time*, resulting in a reduction in the number of hauler ritase.

In the *hauling process*, the impact of *road maintenance mode failure* is a decrease in the quality of the transport road which affects the speed of the tool. Poor road conditions cause the conveyor to not be able to operate at optimal speed, so the travel time increases and the number of conveying cycles in units of time becomes less.

Meanwhile, in the *dumping process, the dense* dumping point *conditions* cause queues of transportation equipment. The main impact of this condition is the increased *queuing time*, which directly increases the duration of delays in the tool's work cycle and decreases the overall efficiency of the operation.

Overall, the impact of the *identified failure modes* shows that the delays that occur are not only local to a single process, but also have a systemic impact on the entire production cycle circuit. This causes the accumulation of unproductive time which leads to a decrease in tool productivity and the failure to achieve production targets.

Thus, the identification of these impacts becomes an important basis for assessing the severity of each *failure mode*, which will then be used in the FMEA analysis to determine the priority of improvement based on *the Risk Priority Number* (RPN) value (Olatunde Omisola et al., 2024).

Table 5. RPN Assessment

Failure Mode	**Effect**	**S**	**O**	**D**	**RPN (S x O x D)**
Repair Front	Loading is stopped so that the actual productivity drops from the target	8	10	5	400
Long Recoil Front Maneuvers	Cycle time increases so that the hauler ritase decreases	4	2	2	16
Narrow Front	The hauler maneuver area is limited so that idle time increases	2	1	2	4
Road Maintanance	Poor road conditions cause the hauler speed to decrease	4	6	6	144
Repair Disposal/ Dumping Point	Waiting time increases so that rritis is reduced	8	5	5	200
Dumping Point Crowded	Waiting time increases so that rritis is reduced	5	4	5	100
Crowded Street	Road conditions that are too congested cause the hauler speed to decrease	4	4	6	96
Front Crowded	The hauler maneuver area is limited so that idle time increases	4	5	7	140

Based on the results of the FMEA assessment in Table 5, an RPN value was obtained for each failure mode which reflects the level of risk relative to the operational performance of Overburden Removal. The 3 highest RPN values in order are Repair Front (400), Repair Disposal/Dumping Point (200), Road Maintenance (144).

Repair Front earned the highest RPN score of 400, which was driven by *Severity* 8 and *Occurrence* 10 values. The *Severity* value of 8 reflects that the contribution of this delay to the total *loss productivity* is very significant, which is 152,088 BCM or around 19.5% of the total loss. The Occurrence value of 10 indicates the frequency of occurrences as many as 1,207 times per year, which is in the highest range on the rating scale. While the *Detection* value of 5 indicates that this event is very difficult to detect or prevent before it occurs. The combination of these three factors makes the Repair Front a top priority that must be addressed immediately.

The second failure mode with the highest RPN value is the Repair Disposal/Dumping Point of 200. The *Severity* value of 8 shows a significant impact in the form of an increase in waiting time for transportation equipment, while *Occurrence* 5 reflects the frequency of events as many as 328 times per year. Although the RPN value is far below the Repair Front, the contribution of *loss productivity* of 107,589 BCM makes this *failure mode* still the second priority that needs attention.

The third failure mode with the highest RPN value is Road Maintenance of 144. The Severity 4 value shows a significant impact, while Occurrence 6 reflects the frequency of events as many as 436 times per year. Although the RPN value is below Repair Disposal, the contribution of loss productivity of 24,409 BCM makes this *failure mode* the next priority that needs attention to maintain the smooth hauling route.

The FMEA data collection methodology in this study uses *a hybrid* approach to ensure the accuracy and objectivity of the results. The *Severity* and *Occurrence parameters* are measured quantitatively based on historical data from the annual production report on site to eliminate subjectivity bias. The scoring of the two parameters refers to the standardization of the internal assessment scale: *the Severity value* is determined based on the percentage of the contribution of constraints to the total *loss productivity*, while the *Occurrence value* is determined based on the frequency range of events in a one-year period.

The Detection Parameters in this study were measured using an expert judgment-based questionnaire involving seven expert respondents, consisting of Operation Supervisors, Foremans, and Engineers with a minimum of three years of work experience. The Detection value was obtained from the average assessment of all respondents, while the Severity parameter was determined based on the contribution of each type of delay to the total production loss, and Occurrence was determined based on the frequency of occurrence of each delay during the study period. These three parameters are used to calculate the Risk Priority Number (RPN) in the Failure Mode and Effects Analysis (FMEA) method as the basis for determining the risk priority level. The results of the analysis showed that the three types of delays with the highest priority value were Repair Disposal/Dumping Point, Repair Front, and Road Maintenance, so these three were set as top priorities to be further analyzed using Fault Tree Analysis (FTA) to identify the root cause and formulate effective repair strategies in minimizing operational delays in the future.

4. **ANALYZE (2): Identify and Analyze Risk Causes using FTA**

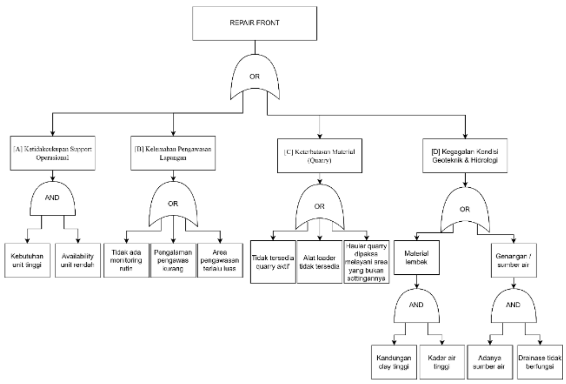

Figure 1. Fault Tree Analysis (FTA) Penyebab Delay Repair Front

Based on *the Fault Tree Analysis* (FTA) presented in the diagram above, the occurrence of the Repair Front as a top event is identified as the result of several groups of major causes that contribute to each other through the logical relationship of AND and OR.

The first cause is insufficient operational support. This factor is modeled by the AND logic gate (Kabir, 2017), which shows that these conditions will only occur if two conditions are met simultaneously, namely high unit demand and low unit availability. This means that even if one of the conditions occurs separately, the impact is not necessarily significant, but the combination of the two simultaneously will directly trigger a lack of operational support in the field (Djenadic et al., 2019; Odeyar et al., 2022).

The second cause is the weakness of field surveillance, which is modeled using the OR logic gate. This suggests that a lack of supervision can occur when one of several causative factors arises, without necessarily occurring simultaneously. These factors include the absence of routine monitoring, lack of supervisory experience, and the extent of the supervision area that is not proportional to the control capacity. This condition reflects that the supervisory aspect has a high sensitivity to various individual weaknesses.

Furthermore, material limitations (*quarry*) are also a significant causative factor and are modeled with OR logic. Based on the diagram, there are three main conditions that can trigger this limitation, namely the unavailability of active quarries, the unavailability of loaders, and conditions where quarry haulers are forced to serve areas that are not their operational settings. These three factors can independently lead to disruption of material supply, which ultimately impacts the readiness and stability of the work front.

The last cause is the failure of geotechnical and hydrological conditions, which is also modeled with OR logic at the main level. This factor is divided into two sub-causes, namely soft material conditions and the presence of puddles or water sources. Both sub-causes have the characteristics of AND logic at the next level. Soft materials occur due to a combination of high clay content and high moisture content, while waterlogging is triggered by the presence of water sources (groundwater or runoff) that are not balanced with a properly functioning drainage system. This shows that geotechnical and hydrological factors are not only influenced by natural conditions, but also by the effectiveness of technical management in the field.

Overall, this shows that *the Repair Front* is the result of a complex interaction between operational factors, supervision, resource availability, and geotechnical and hydrological conditions. Therefore, improvement efforts cannot be carried out partially, but an integrated approach is needed by considering the identified cause-and-effect relationships.

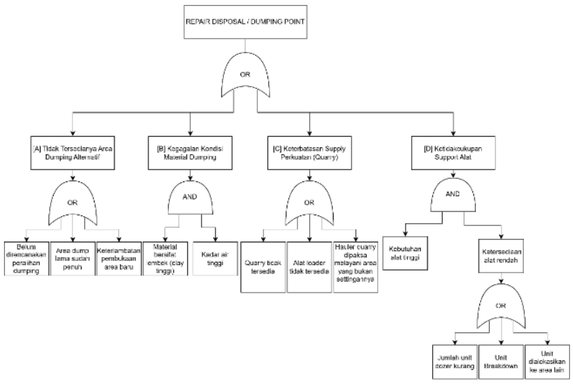

Figure 2. *Fault Tree Analysis* (FTA) Causes *Delay Repair Disposal*

Based on the *Fault Tree Analysis* (FTA) presented in the figure above, *the Repair Disposal/Dumping Point* occurrence as the *top event* was identified as a result of several groups of major causes contributing to each other through the logical relationship of AND and OR.

The first cause is the unavailability of alternative dumping areas, which are modeled using the OR logic gate. This suggests that the condition can occur if one of several causative factors appears. These factors include unplanned dumping switches, old dumped areas that are already full, and delays in opening new areas. Each of these factors can independently cause the unavailability of alternative areas, so that dumping activities are hampered and have the potential to cause the need for *repair disposal*.

The second cause is the failure of the dumping material condition, which is modeled by the AND logic gate. This shows that this failure occurs when two conditions occur simultaneously, namely soft materials (have a high clay content) and high moisture content.

The combination of these two factors causes materials to lose their carrying capacity, so that they are unable to withstand the load of heavy equipment and stockpile materials, which ultimately triggers instability in the disposal area.

Furthermore, the limited supply of reinforcement (quarry) is also one of the main causes modeled with OR logic. Based on the diagram, this condition can be triggered by the unavailability of quarry, the unavailability of loaders, and conditions where the quarry hauler is forced to serve areas that are not its operational setting. These three factors can independently inhibit the provision of reinforcement materials needed to maintain the stability of the dumping point.

The fourth cause is the inadequacy of the tool's support, which is also modeled with the OR logic gate. This shows that the limitations of the tool can occur due to several factors, such as soft material conditions, low unit availability, and the presence of puddles or water sources in the work area. Furthermore, the low unit availability factor is derived again in the form of OR logic, which consists of a low number of dozer units, units experiencing breakdowns, and units being allocated to other areas. This shows that the problem of tool availability is not only influenced by the number of units, but also by the reliability aspect of the tool and its operational distribution.

Overall, this FTA shows that *repair disposal* incidents are the result of complex interactions between aspects of operational planning, material and environmental conditions, availability of material resources, and heavy equipment support in the field. Therefore, control efforts cannot be carried out partially, but require an integrated approach, starting from more adaptive dumping planning, material condition management, *quarry supply optimization*, to improving the management and allocation of heavy equipment effectively.

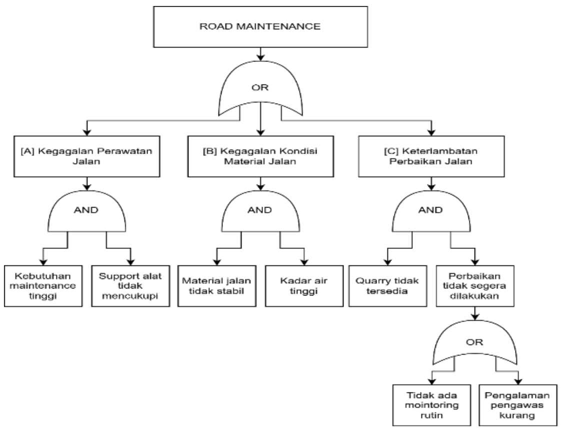

Figure 3. Fault Tree Analysis (FTA) Penyebab Delay Road Maintenance

Based on the *Fault Tree Analysis* (FTA) presented above, *road maintenance incidents* in the form of damaged roads or requiring repairs as top events are identified as the result of several groups of main causes that contribute to each other through the logical relationship of AND and OR.

The first cause is road maintenance failure. This factor is modeled using the AND logic gate, which shows that maintenance failures will only occur if two conditions are met simultaneously, namely high maintenance requirements and insufficient tool support. The high maintenance needs reflect the intensity of road damage that requires more frequent handling than normal conditions. However, if it is not balanced with the availability of adequate equipment, then maintenance activities cannot be carried out optimally. Furthermore, the limited support of this tool is modeled by OR logic, where one of the main causes is the unavailability of dozer units. This shows that the absence of an independent lock tool is enough to trigger a failure in the implementation of road maintenance.

The second cause is the failure of the road material condition, which is modeled using the AND logic gate. This shows that road damage due to material factors occurs when two conditions appear simultaneously, namely unstable road materials and high moisture content. Unstable materials have low bearing capacity so they are prone to deformation when passed by heavy equipment. This condition is exacerbated by the high moisture content, which in this FTA structure is further explored as a result of previous rains. Thus, environmental factors play a role as a trigger that accelerates the decline in the quality of road structures, especially in materials with water-sensitive characteristics.

The third cause is the delay in road repairs, which is also modeled with the AND logic gate. This shows that delays only occur when road damage has occurred and no immediate repair action is taken. The "no immediate repairs" condition is further modeled with OR logic, which indicates that the delay can be triggered by one of two factors, namely the lack of quarry support or the slow response time of the supervisor. The lack of quarry support is related to the limited availability of repair materials, so repair activities cannot be executed immediately. Meanwhile, the slow response of supervisors reflects weaknesses in the operational supervision system, especially in detecting and responding to road damage conditions quickly.

Overall, this FTA shows that road maintenance problems are the result of interactions between operational factors, tool availability, material characteristics, environmental influences, and the effectiveness of responses in the field. Therefore, improvement efforts cannot be carried out partially, but rather require an integrated approach taking into account the cause-and-effect relationships that have been identified in this FTA structure.

5. IMPROVE: Improvement Strategy (Mitigation)

After conducting *a Fault Tree Analysis* (FTA) to identify the *root cause* of the *Delay* problem that occurs, the next stage is to formulate improvement steps that can be applied to reduce and even eliminate *Delay* in operational activities in the field. Each identified root of the problem of the three types of *delay* is systematically elaborated into an analysis table to determine a targeted solution, so that it is expected to contribute to a sustainable increase in *overburden* (OB) production.

The method used in formulating solutions to the various root problems is *Focus Group Discussion* (FGD). This FGD activity involved the author and *the mine operation* and *engineering* team, with a total of 7 participants representing across departments, namely *foreman mine operation*, *engineering*, and *dispatch*. This multidisciplinary approach was chosen to ensure that the resulting solution was comprehensive and considered the perspectives of the various operational functions involved.

Based on the results of the analysis of the Improve stage, various mitigation strategies were formulated to address the root causes of the three types of priority delays, namely Repair Front, Repair Disposal, and Road Maintenance. Improvement recommendations include operational and managerial aspects, such as the addition and allocation of support equipment (dozers, excavators, loaders, and haulers), the preparation of preventive maintenance schedules that do not interfere with production hours, the provision of spare equipment, the increase in the availability of quarry materials, the construction and maintenance of drainage, the preparation of standard operating procedures (SOPs) for supervision, the implementation of training for field supervisors, and the strengthening of coordination between divisions and the implementation of Operational Discipline. Each mitigation alternative is evaluated based on implementation needs and cost consequences, resulting in a combination of actions that are not only effective in reducing delays, but also feasible from an operational and economic point of view.

The results of the focused discussion with the Department of Mine Operation, Engineering, and Dispatch showed that the main causes of operational delays in the three categories came from three dominant factors, namely the low effectiveness of field supervision, the limited number of support tools, and the lack of supply of quarry materials to support the improvement of the front, disposal, and transportation areas. These three factors are interrelated so that they form an interdependent relationship. The limitation of quarry materials leads to a decrease in the quality of roads which increases the need for support equipment, while weak supervision hinders early detection of problems that arise in the field. Therefore, the implementation of mitigation strategies needs to be carried out in an integrated and simultaneous manner in order to eliminate the root cause comprehensively, prevent bottleneck transfers between processes, and increase productivity and operational efficiency of overburden stripping in a sustainable manner.

Furthermore, based on the plan and estimates that have been agreed upon by the internal team through the FGD, the implementation of the mitigation strategy is targeted to be able to reduce the total duration of delay by 30% from the baseline average of 1.40 hours per shift. Thus, the remaining duration of delay after mitigation is applied is projected to be 1.40 × 70% = 0.98 hours per shift and for 0.98 hours the support package is calculated to be in active operation. This approach is the basis for calculating the annual equipment rental cost in the BCR analysis (Machairas & Varouchakis, 2023; Trijayanto & Hakam, 2025), where the total rental hours per year are obtained from 0.98 hours × 722 shifts = 707.56 hours per year, which reflects more efficient operational conditions than existing conditions after the mitigation strategy has been implemented consistently in the field.

6. **CONTROL: Control/Monitoring Plan**

The Control Phase is the final stage in the DMAIC framework which aims to ensure that the improvements that have been formulated in the Improve stage can be implemented consistently and have a sustainable impact on operational performance. Without a structured control mechanism, there is a risk that field conditions will return to their original state after the initial implementation period ends. Therefore, a control system was designed that includes the determination of performance indicators, layered monitoring mechanisms, escalation systems, and continuous improvement cycles.

a. **Penetapan KPI (Key Performance Indicator) Delay**

As a basis for measurable control, key performance indicators are established that refer to the baseline historical data in Table 4.18. This KPI serves as an objective reference in assessing the effectiveness of the implementation of the mitigation strategy that has been prepared.

Table 4. *Key Performance Indicator Plan*

Yes	Jenis Delay (Controllable)	Baseline Duration (Hours/Months)	FrekuensiMonitoring	PICUtama
1	Repair Front	45,24	Per Shift	Foreman Loading
2	Repair Disposal/ Dumping Point	32,03	Per Shift	Foreman Disposal
3	Road Maintenance	7,27	Per Shift	Foreman Area
	TOTAL	84,54		

The *baseline values* in the table above represent the actual operational conditions during the observation period. Any increase in the duration of *the delay* that exceeds the baseline value in the current period is an early signal that the mitigation strategy is not running optimally and requires further evaluation.

b. Layered Monitoring Mechanism

The monitoring system is designed in three layers based on the hierarchy of the mine operational organization, with different frequencies and depths of analysis at each layer.

Daily Monitoring (Foreman Level)

Whenever there are obstacles in the field, the foreman is responsible for recording all delays that occur during the shift into the daily operational report. Recording includes the type of *delay*, start and finish time, duration, causes identified in the field, and handling actions that have been taken. This data is the main input for the weekly and monthly recaps. Recording discipline at this level is crucial because it is a primary data source that determines the accuracy of the entire monitoring process on it.

Weekly Monitoring (Supervisor Level)

At the beginning of each week, operational supervisors review the recap of data delay for the previous seven days. This review includes a comparison of the duration and frequency of actual delays to the previous week, identification of trends that show improvement, and verification of whether planned mitigation actions have been implemented in the field. If indications are found that a particular delay has increased consistently for two consecutive weeks, the *supervisor* is required to conduct a field investigation and report the results to the *Engineer*.

Monthly Monitoring (Engineer and Mine Superintendent Level)

At the end of each month, *the Engineer* prepares a comprehensive evaluation report that compares the actual performance of the current month against the historical baseline in Table 4.18 This report is presented in a monthly evaluation meeting involving *the Mine Superintendent*, *Supervisor*, and representatives of *the Engineering* department and *Dispatch*. In this meeting, the effectiveness of the mitigation strategy that is running, the implementation obstacles encountered in the field, and the need to adjust the follow-up plan for the next month were discussed.

CONCLUSION

Based on the results of the study, it was concluded that the application of the Lean approach, Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Benefit-Cost Ratio (BCR) analysis successfully identified and prioritized the main causes of production losses in the overburden removal process. The identification results revealed a production loss of 779,403 BCM, of which 51.4% originated from controllable delays that could potentially be reduced through targeted improvement efforts. The FMEA analysis identified Repair Front, Repair Disposal, and Road Maintenance as the highest-priority risks, while the FTA analysis demonstrated that the root causes of delays were not only related to technical factors but were also influenced by human factors, work methods, supervisory effectiveness, and resource limitations. Based on the Improve phase of the DMAIC framework and BCR analysis, the strategy of adding support equipment in priority areas was considered the most feasible improvement alternative because it provided economic benefits with a BCR value of 1.53 (Deesrisak et al., 2019). Future research is recommended to develop more adaptive standard operating procedures (SOPs), validate mitigation strategies on a broader operational scale, and strengthen human resource management to ensure that improvement initiatives can sustainably enhance operational efficiency and productivity.

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