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Lean Six Sigma Improvement for Reducing Material Storage in Underground Mine at PT Freeport Indonesia

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Abstract
Material availability is essential for underground mining operations; however, fragmented storage, limited inventory visibility, and delivery delays can disrupt production and increase operational waste. This study aimed to identify the root causes of inventory control and storage management issues for ground support materials at the Grasberg Block Cave, Kucing Liar, and Deep Mill Level Zone mines of PT Freeport Indonesia and to formulate prioritized improvement strategies. A case study approach was conducted using the Lean Six Sigma DMAIC framework, incorporating observations, 5S assessments, questionnaires, semi-structured interviews, operational records, Value Stream Mapping, Pareto analysis, Current Reality Tree analysis, Action Priority Matrix, and Impact-Complexity Analysis. The findings showed that waiting was the dominant waste, with a score of 115, followed by inventory waste with a score of 98; together, these two categories accounted for 44.9% of the identified waste. Six of seven storage locations were rated as fair or poor. Four root causes were identified: the absence of standardized inventory management, inadequate control and staffing in shadow storage areas, weak storage and 5S standards, and limited availability of transportation equipment. Dedicated storemen achieved the highest Impact-Complexity Ratio score of 3.23, followed by 5S compliance at 2.59 and daily inventory reporting at 1.91. The study concludes that implementing these initiatives can strengthen traceability, accessibility, inventory accuracy, and material flow reliability across mining operations.

INTRODUCTION

Material availability is a critical factor in ensuring the continuity of underground mine development and production activities. Underground mining operations rely on the timely supply of consumable materials to support development, ground support installation, rehabilitation, and production processes. Ineffective inventory control and storage management can disrupt operational activities through material shortages, delayed access to critical resources, increased operational costs, and reduced productivity. Therefore, maintaining reliable material availability while controlling inventory levels is essential for sustaining operational performance in underground mining environments (Huerta et al., 2022; Khazaei et al., 2025; Samatemba et al., 2020; Sekgetho, 2025; Sishi & Telukdarie, 2020; Walker, 2023).

PT Freeport Indonesia (PTFI) operates several underground mines, including Grasberg Block Cave (GBC), Kucing Liar (KL), and Deep Mill Level Zone (DMLZ), which require substantial volumes of consumable ground support materials to support daily operations. To ensure material availability near the point of use, materials are distributed through multiple underground storage locations managed by different operational groups.

As underground mining operations have expanded, the number of storage locations has increased based on local operational requirements, resulting in fragmented storage conditions and the emergence of shadow storage areas. Although this approach was initially intended to improve material accessibility, it has also increased operational complexity and created challenges related to inventory visibility, inventory control, storage governance, and material traceability. Field observations indicate that materials are often dispersed across multiple storage locations, some of which are not fully controlled, monitored, or managed according to established storage standards. These conditions increase the risks of stockouts, duplicate inventory, material damage, inefficient storage utilization, and delays in material retrieval and distribution (Ambrusevič, 2026; Ernest, 2024; Hasmee et al., 2026; Mostofa, 2024; Mwizerwa & Akumuntu, 2024).

Several issues identified during this study indicate weaknesses in the current storage management system. The 5S assessment revealed significant gaps in storage organization, standardization, and material control across multiple underground storage locations. Storage inspections also identified uncontrolled materials and unauthorized storage areas, while material movement reporting was found to be inconsistent, resulting in limited inventory visibility and inaccurate inventory information. In addition, the Value Stream Mapping (VSM) analysis showed that the material delivery process remained dominated by waiting time and other non-value-added activities. Voice of Customer (VoC) findings also highlighted material delivery delays, stockout incidents, and poor inventory visibility as the main concerns among operational users. These findings indicate that the current storage management process has not consistently ensured that materials are available, traceable, and accessible when required (Asante et al., 2021; Karaduman & Gülhas, 2025; Omar et al., 2022; Zeng et al., 2024; Zhu et al., 2025).

Previous studies have shown that Lean Six Sigma can be effectively applied to improve operational performance in manufacturing, oil and gas, and mining industries. However, relatively few studies have focused on inventory control and storage management in underground mining operations, particularly issues related to fragmented storage, inventory visibility, material traceability, and storage governance. As underground mining operations continue to expand, these challenges become increasingly important because they directly affect material availability and operational performance. Therefore, a structured improvement approach is required to identify the root causes of these issues and develop practical solutions that improve material availability while reducing unnecessary inventory and storage-related waste (Daniyan et al., 2023; Dolch et al., 2026; Sathursiya et al., 2026; Senanayaka, 2025; Welarathna, 2026).

This study aimed to identify the root causes of ineffective inventory control and storage management in underground mining operations and develop improvement recommendations using the Lean Six Sigma DMAIC (Define, Measure, Analyze, Improve, and Control) framework. A case study was conducted on the management of consumable ground support materials in the GBC, KL, and DMLZ mines at PT Freeport Indonesia. This study is expected to contribute to both the application of Lean Six Sigma in mining logistics and practical decision-making related to inventory control and storage management in underground mining operations.

METHOD

Research Design

The research framework consisted of five sequential phases based on the Lean Six Sigma DMAIC approach. The Define phase identified operational problems and customer requirements, the Measure phase assessed current process performance and waste sources, the Analyze phase determined the root causes of identified problems, the Improve phase developed and prioritized alternative solutions, and the Control phase established implementation and monitoring mechanisms to support sustainability. The overall research design is presented in Figure 1.

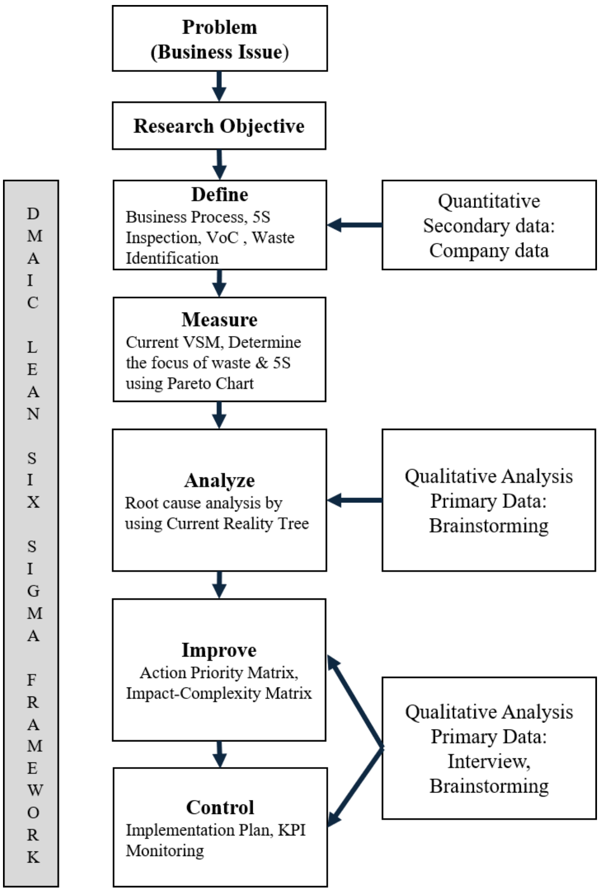

Figure 1. Research Design

Data Collection Method

The study utilized both primary and secondary data sources. Primary data were collected through direct field observations, 5S assessments, questionnaires, semi-structured interviews, and discussions with key stakeholders and Subject Matter Experts (SMEs) involved in material planning, logistics operations, warehouse management, and underground mining activities. Secondary data included inventory reports, material delivery records, storage inspection results, historical operational data, and company documents related to material management processes. The combination of these data sources enabled a comprehensive assessment of existing inventory control and storage management practices.

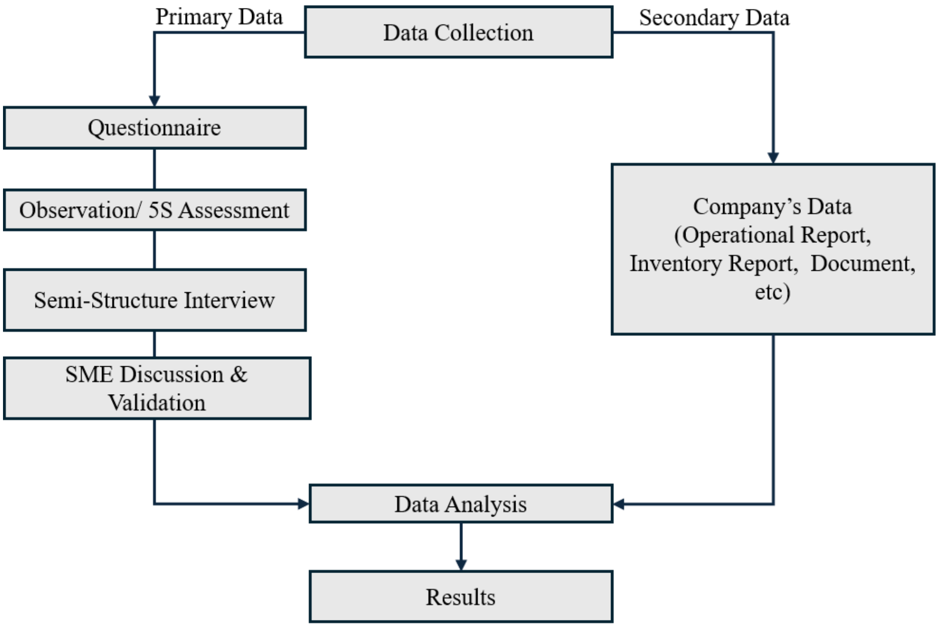

Figure 2. Data Collection Method

Data Analysis

The DMAIC framework was implemented using a combination of qualitative and quantitative analysis techniques. During the Define phase, Process Mapping, Voice of Customer (VoC), and waste identification were applied to understand operational challenges and customer expectations. In the Measure phase, Value Stream Mapping (VSM), Pareto Analysis, and 5S assessments were used to evaluate current process performance and identify major inefficiencies. In the Analyze phase, a Current Reality Tree (CRT) was developed and validated through stakeholder interviews and SME discussions to identify the root causes of poor inventory control and storage management. During the Improve phase, alternative improvement initiatives were generated and evaluated using an Action Priority Matrix and Impact-Complexity Analysis to determine implementation priorities. Finally, the Control phase developed an implementation roadmap, Key Performance Indicators (KPIs), and monitoring mechanisms to support the sustainability of the proposed improvements.

Table 1 presents the analytical tools applied at each stage of the DMAIC framework to support systematic problem identification, root cause analysis, and decision making throughout the improvement process.

Table 1. Data Analysis Method

Stage	Method of Analysis
Define	Process Mapping, 5S Assessment, Voice of Customer, Waste Identification
Measure	Value Stream Mapping, Pareto Chart
Analyze	Current Reality Tree,
Improve	Action Priority Matrix, Impact-Complexity Analysis
Control	Control Plan, KPI Monitoring Framework, Performance Dashboard

RESULTS AND DISCUSSION

Define Phase

The Define phase was conducted to evaluate the current inventory control and storage management practices within underground mining operations.

Business Process of Delivery Material Underground

Field observations reveal a significant gap between the design process and its actual implementation. The min–max inventory system, storage inspections, and material movement reporting are not consistently applied, resulting in limited inventory visibility and inadequate control of material flow. Consequently, material distribution tends to be reactive, increasing the risk of overstock, stockout, material accumulation, and inefficient storage utilization. These findings indicate that current material management practices have not fully achieved the intended level of control and visibility, providing a clear opportunity for improvement through Lean Six Sigma initiatives aimed at reducing underground inventory and improving material flow efficiency.

Underground Storage Conditions Based on 5S Inspection

A 5S assessment was conducted across seven underground storage locations. The results showed that six of the seven assessed locations were classified as either Fair or Poor, indicating substantial deficiencies in storage organization, standardization, housekeeping, and material control practices.

Table 2. Summary of Assessment Score

No	Area	SEIRI (Sort)	SEITON (Set in Order)	SEISO (Shine)	SEIKETSU (Standardize)	SHITSUKE (Sustain)	Total Score per Area	Maximum Score per Area
1	GBC_GVD 3 Old Alimak	3	5	3	4	5	20	50
2	GBC_GVD 4 XC 5	3	4	5	4	5	21	50
3	GVD_3 XC 5	4	0	5	3	5	17	50
4	GVD_2/3 XC 4	4	1	5	3	5	18	50
5	GBC_UC - New Office Alimak	7	3	6	5	6	27	50
6	KL_MB# 8	4	5	4	4	5	22	50
7	DMLZ_Banti, Cement & Mesh Storage	9	7	7	8	8	39	50

Based on Table 2, each element consists of five criteria, the maximum score for an individual 5S element is 10 points, resulting in a maximum or ideal overall score of 50 points across all five 5S elements for each storage area. The total score per area was used to assess the maturity level of 5S implementation within material storage areas. Scores of 45–50 were categorized as Excellent (Best Practice), 35–44 as Good (Minor Improvement Required), 25–34 as Fair (Corrective Action Required), and below 25 as Poor (Immediate Action Required). The findings indicate significant variation in storage management performance across underground storage locations. Common issues identified during the assessment include poor material organization, inadequate storage standardization, inconsistent housekeeping practices, and weak inventory control. These conditions reduce material visibility and accessibility and may contribute to inventory inaccuracies, stockouts, and inefficient storage utilization.

Material Movement Reporting Practices

Assessment of material movement reporting practices revealed several critical gaps. Material-out transactions were generally not recorded, daily inventory reporting was not implemented, and inventory information was often inaccurate or incomplete. As a result, inventory visibility remained limited, making it difficult to monitor material movement and maintain inventory accuracy. These issues contributed to stock discrepancies and operational inefficiencies across underground mining operations.

Voice of Customer

To understand operational requirements, a Voice of Customer (VOC) assessment was conducted among planners and operational personnel across GBC, KL, and DMLZ mines. The results identified three key customer requirements: material availability, material delivery reliability, and inventory visibility. Respondents highlighted frequent stockouts, delivery delays, and difficulties in locating materials as the most significant issues affecting operational performance. These findings indicate that ensuring material availability, accessibility, and visibility should be the primary focus of improvement efforts.

Table 3. Voice of Customer to Critical to Quality (VOC–CCR Mapping)

No.	Main Customer Requirement Category	Voice of Customer (VOC)	Customer Critical Requirement (CCR)
1	Material Delivery Reliability	Users expect materials to be delivered on time and according to operational requirements. However, delays in material delivery are still experienced and may disrupt work execution and operational continuity.	Materials must be delivered on time and according to operational requirements.
2	Material Availability	Users frequently experience material shortages and stockout incidents that affect operational activities. As a result, users often need to request materials earlier or in larger quantities to ensure material availability when required.	Materials must be available when needed to support uninterrupted operations.
3	Inventory Visibility and Administrative Efficiency	Users face challenges in locating materials, monitoring inventory status, and completing administrative processes efficiently. Inaccurate inventory records and complex administrative activities often lead to additional effort and reduced process efficiency.	Materials and inventory information must be easily accessible, accurate, and visible to users.

Waste identification

To identify the main sources of inefficiency in the material management process, a waste assessment was conducted using the DOWNTIME framework. The assessment involved operational personnel and material planners from GBC, KL, and DMLZ mines. The results showed that Waiting was the most significant waste category, with a total score of 115, followed by Inventory (98) and Overproduction (70). Together, these categories represented the largest contributors to process inefficiencies in underground material management.

Table 4. Summary of Waste Identification Results

No	Waste	Total Score
1	Waiting	115
2	Inventory	98
3	Overproduction	70
4	Extra Processing	50
5	Transportation	48
6	Non-Utilized Talent	44
7	Motion	29
8	Defect	20

The high Waiting score indicates that material delivery delays and slow responses to material requests continue to affect operational performance. The Inventory score highlights issues related to stockout risk, limited inventory visibility, inventory inaccuracies, and ineffective storage practices. Meanwhile, Overproduction reflects the tendency of users to request materials earlier or in larger quantities than necessary as a precaution against potential shortages and delivery delays. These findings suggest that improving inventory visibility, material availability, and material flow reliability should be the primary focus of subsequent analysis and improvement efforts.

Measure Phase

Following the identification of the key issues during the Define phase through business process analysis, storage inspections, Voice of Customer assessment, and waste identification, the study proceeded to the Measure phase. This phase evaluated current process performance and prioritized the most significant sources of inefficiency using Value Stream Mapping and Pareto Analysis.

Value Stream Mapping

Value Stream Mapping was used to examine the end-to-end flow of consumable ground support materials from planning and preparation to transportation and underground storage. The analysis measured lead time, cycle time, waiting time, value-added time, non-value-added time, and business non-value-added time for weekly planned materials and additional material requests in DMLZ and GBC/KL.

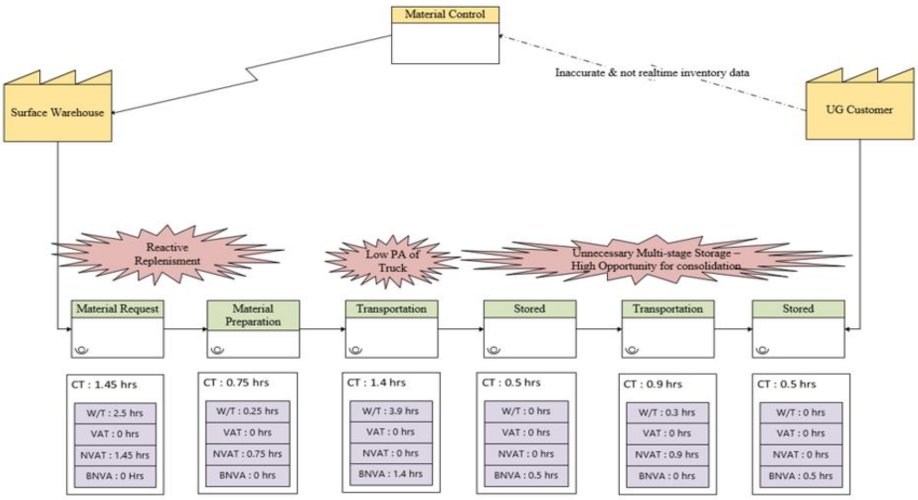

Figure 3. Current Value Stream Mapping Delivery material to DMLZ Mine

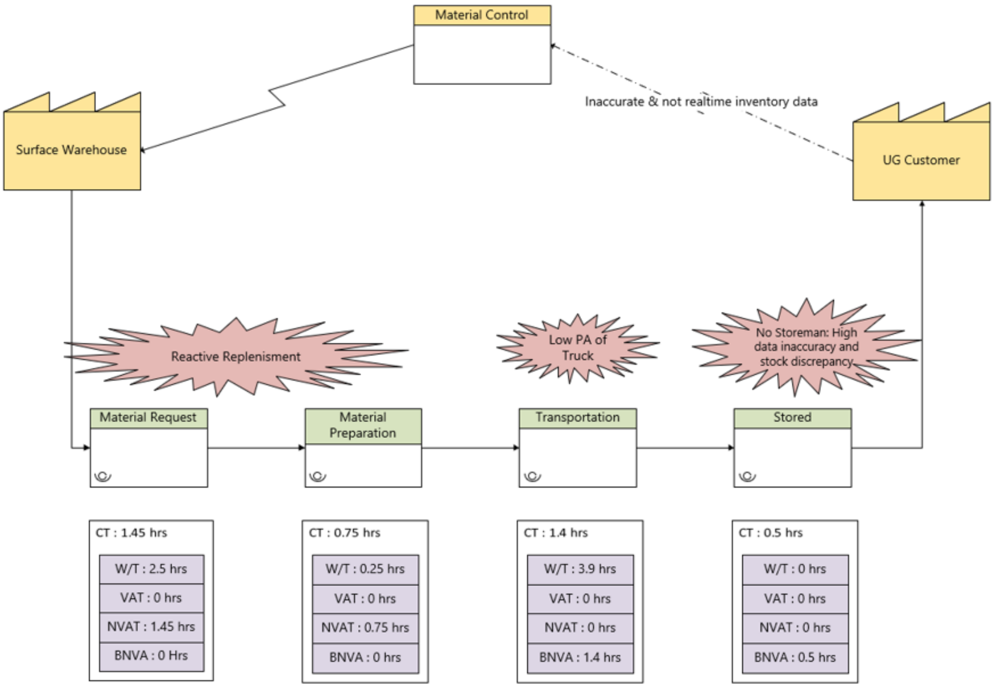

Figure 4. Current Value Stream Mapping Delivery material to GBC or KL Mine

Table 3. Comparison of Current-State VSM Results

Mine Area	Material Flow	Lead Time	Cycle Time	Waiting Time	NVAT	BNVAT
DMLZ	Weekly Plan	7.5	3.3	4.1	1.4	1.9
DMLZ	Additional Material	11.7	5.8	5.9	3.9	1.9
GBC/KL	Weekly Plan	5.8	1.9	3.9	0	1.9
GBC/KL	Additional Material	10.1	4.4	5.6	2.5	1.9

Note: All values are expressed in hours. NVAT = Non-Value-Added Time; BNVAT = Business Non-Value-Added Time.

The results indicate that DMLZ primarily requires process simplification and the reduction of redundant storage stages, whereas GBC/KL requires stronger inventory control, clearer storage ownership, and more reliable inventory information. Both areas require improvements in material-flow coordination and inventory visibility to reduce waiting time and support more responsive material distribution.

Pareto Analysis of Operational Waste

Pareto Analysis was used to prioritize the waste categories identified during the Define phase.

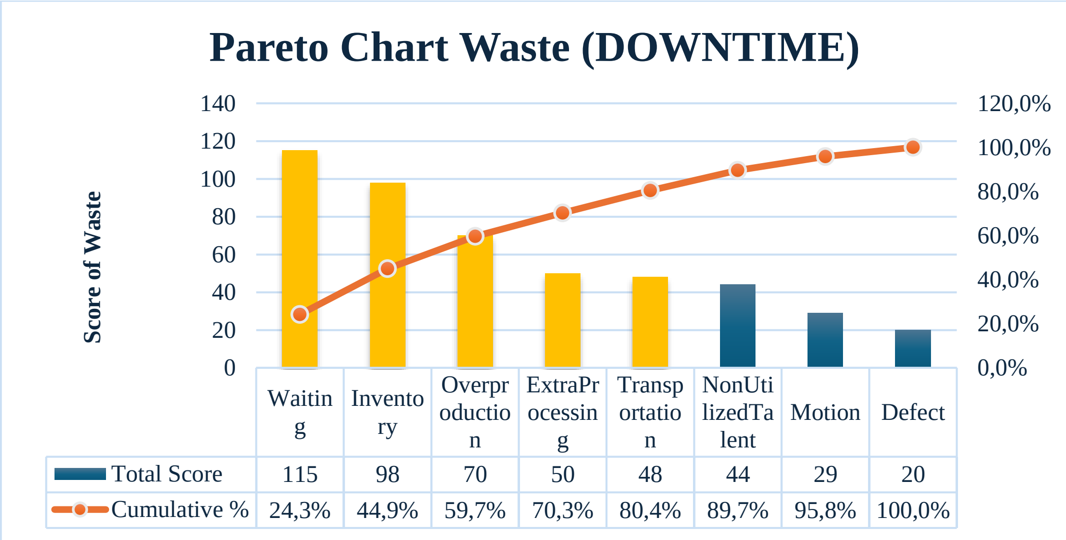

Figure 5. Pareto Diagram Analysis of Waste

The Pareto analysis identified Waiting as the largest source of operational waste, with a score of 115 or 24.3% of the total, followed by Inventory with a score of 98. Together, these categories accounted for 44.9% of the identified waste. Overproduction and Extra Processing increased the cumulative contribution to 70.3%.

Although Overproduction ranked third, the findings suggest that excessive material requests were primarily a response to uncertainty in material availability, stockouts, and delivery delays rather than an independent root cause. Therefore, Waiting, Inventory, and Extra Processing were selected as the main issues for further investigation during the Analyze phase.

Pareto Analysis of 5S Gaps

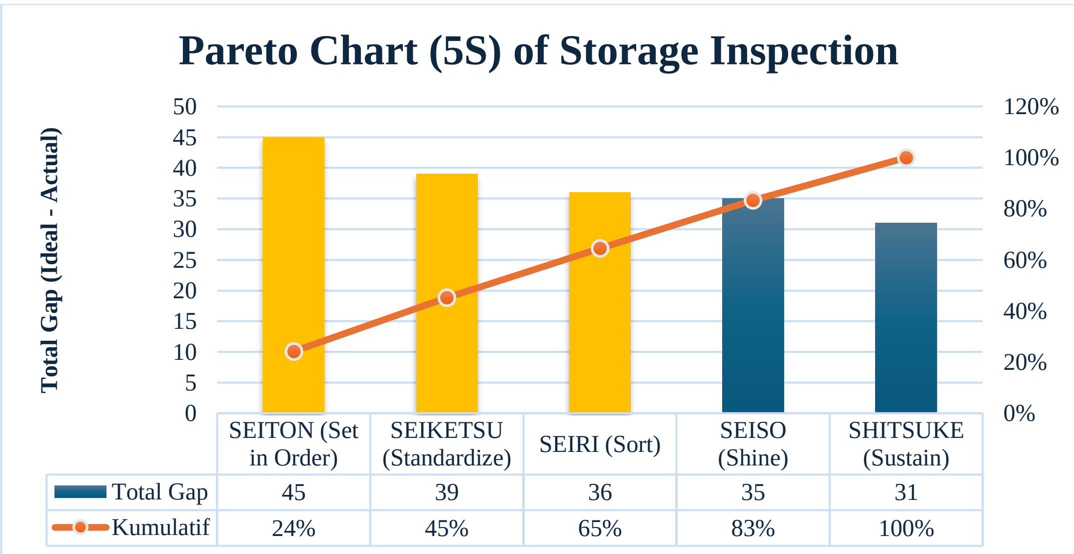

Figure 6. Pareto Diagram Analysis of 5S

The Pareto analysis showed that Seiton (Set in Order) represented the largest 5S gap, with a gap score of 45, followed by Seiketsu (Standardize) with 39 and Seiri (Sort) with 36. Together, these three elements accounted for approximately 65% of the total 5S gap. Therefore, material arrangement, storage standardization, and the separation of necessary and unnecessary materials were identified as the primary areas requiring improvement.

The large gap in Seiton (Set in Order) suggests that materials are not arranged systematically, making it difficult for users to find and retrieve the required items. This condition can increase material search time and potentially delay operational activities. Likewise, the gap in Seiketsu (Standardize) indicates that standard procedures for storage management have not been implemented consistently, resulting in variations in work practices and longer lead times. The gap in Seiri (Sort) further shows that materials are not adequately separated based on their usage requirements. As a result, necessary and unnecessary materials may be mixed, creating inefficiencies and increasing the risk of inventory inaccuracies, stockouts, and overstock situations.

Overall, the Measure phase identified two major areas requiring further analysis. First, excessive waiting time and non-value-added activities affected the material distribution process, particularly additional material requests. Second, weaknesses in material arrangement, standardization, and sorting reduced the effectiveness of storage management. These findings provided the quantitative basis for the Current Reality Tree analysis conducted during the Analyze phase.

Analyze Phase

After identifying the major issues in the Define and Measure phases, the next step was to analyze the underlying causes of poor inventory control and storage management. This phase aimed to answer the first research question by identifying the root causes that lead to material unavailability, poor inventory visibility, and storage management inefficiencies. To support this analysis, a Current Reality Tree (CRT) was developed based on the findings from business process observations, 5S assessments, Value Stream Mapping, waste identification, and Voice of Customer analysis. The CRT was then validated through interviews and discussions with stakeholders and Subject Matter Experts (SMEs).

Current Reality Tree

The CRT analysis identified “Material Not Available, Traceable, or Accessible When Needed” as the primary problem within the current material management system. This condition reflects situations where materials required for operational activities are either unavailable, difficult to locate, or cannot be accessed on time. The analysis showed that this issue was caused by several interconnected operational problems, including inventory planning failure, poor material traceability, damaged or scattered materials, and material delivery delays.

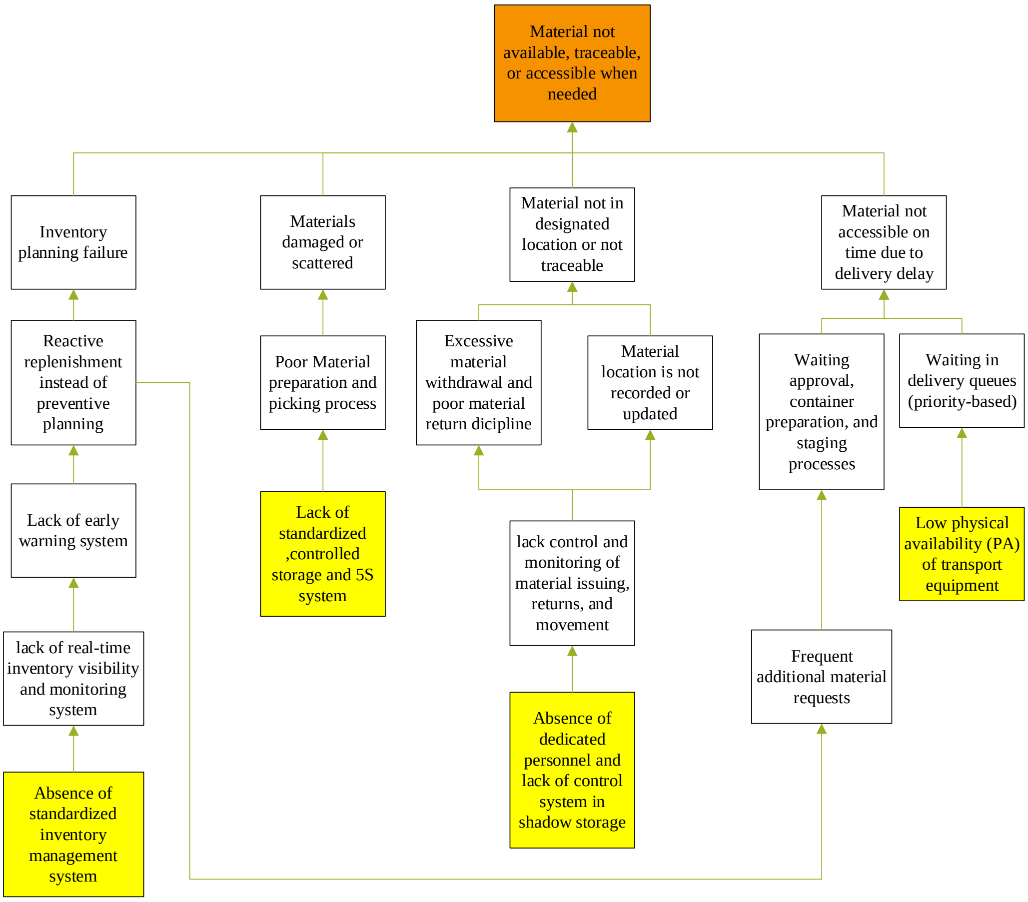

Figure 7. Current Reality Tree

Based on the logical structure of the Current Reality Tree (CRT), four underlying core problems were identified as the root causes of ineffective inventory and storage management:

a. Absence of standardized inventory management system.
   Inventory information was not consistently updated, and material movement reporting was not fully implemented. As a result, inventory visibility was limited and replenishment decisions were often reactive rather than proactive. This situation increased the risk of stock shortages and reduced the accuracy of inventory planning
b. Absence of dedicated personnel and lack of control system in shadow storage
   Many fragmented and shadow storage areas did not have dedicated personnel responsible for controlling material transactions and storage conditions. Material movements were often not recorded properly, making it difficult to identify actual material locations and inventory status. This condition contributed to poor material traceability and inventory discrepancies.
c. Lack of standardized, controlled storage and 5S system
   The 5S assessment revealed weaknesses in material organization, storage standardization, and storage discipline. Materials were frequently stored in inappropriate locations, mixed with other items, or left without proper identification. These conditions increased material search time, reduced storage efficiency, and increased the risk of material damage.

d. Low physical availability (PA) of transport equipment
Material delivery performance was constrained by the limited availability of transportation equipment. Delivery queues and delays frequently occurred, particularly for additional material requests. This condition increased waiting time and reduced material accessibility at underground work areas.

The findings indicate that the identified issues are closely related and reinforce each other. Limited inventory visibility affects planning accuracy, weak storage control reduces material traceability, poor storage practices contribute to material damage and inefficient retrieval, while transportation constraints delay material delivery. Together, these conditions result in materials not being available, traceable, or accessible when required. Therefore, the four root causes identified in this phase became the foundation for developing improvement initiatives in the Improve phase.

Improvement Phase

Based on the root causes identified during the Analyze phase, several improvement initiatives were developed to address inventory control and storage management issues. The proposed solutions were generated through discussions with stakeholders and Subject Matter Experts (SMEs) and evaluated using an Action Priority Matrix and Impact-Complexity Analysis. The objective of this phase was to identify practical initiatives that could improve material availability, inventory visibility, material traceability, and storage governance within underground mining operations.

Proposed Solution Improvement

The analysis identified six main improvement initiatives designed to address the four root causes identified in the CRT analysis.

Table 4. Matrix of Proposed Business Solution and Target Operational Impact

No	Root Cause (Analyze Phase)	Proposed Business Solution (Improve Phase)	Target Output or Impact
1	Absence of Standardized inventory management system	Daily Inventory Report (Min-Max & Movement), Dashboard Material, Integrated Material Visibility and Tracking System (Application/Software)	Achieving highly real-time inventory visibility and establish an automated early warning system for optimal stock replenishment.
2	Lack of standardized, controlled storage and 5S system	Re-layout Storage, Storage Centralization, Storage Inspection, Box/Skid Package per Heading, Install Overhead Crane	Optimizing storage utilization and eliminating material damage through standardized layouts and structural 5S compliance
3	Absence of dedicated personnel and lack of control system in shadow storage	Dedicated Storeman, Storage Centralization, Gate Control (Fence & CCTV), Return of Remaining Material, Repacking Material,	Ensuring highly material traceability and strict transaction control over material issuing and returns in shadow storage, thereby directly securing the data integrity and accuracy of daily inventory report (Min Max & Movement)

No	Root Cause (Analyze Phase)	Proposed Business Solution (Improve Phase)	Target Output or Impact
4	Low Physical Availability of transportation equipment	Transportation capacity improvement, Additional or Replace Truck.	Eliminating delivery delays and supply queues by stabilizing transport equipment availability and streamlining distribution routes

The proposed initiatives are intended to improve inventory visibility, strengthen storage governance, reduce storage fragmentation and enhance material availability, traceability, accessibility within underground mining operations.

Action Priority Matrix

To evaluate and prioritize the recommendations gathered from interviews and questionnaires, an Impact-Effort Matrix was utilized. Each proposed solution was scored by respondents based on its average expected impact and the estimated effort required for implementation. The results of the assessment are presented in Figure 8.

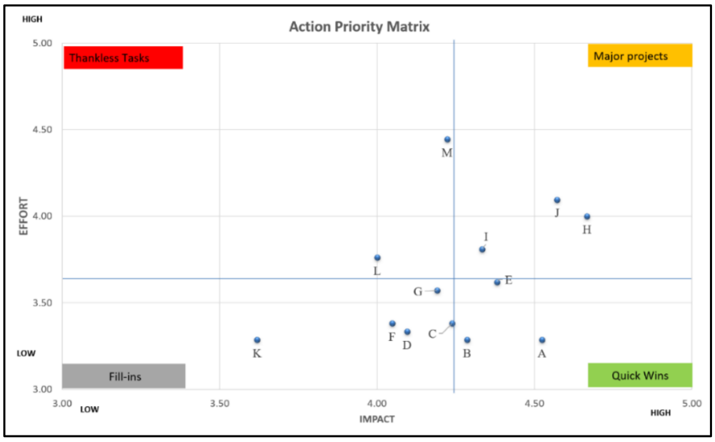

Figure 8. Action Priority Matrix

Based on the Action Priority Matrix shown in Figure 9, each improvement recommendation was mapped according to its impact and implementation effort and subsequently classified into four quadrants. The resulting prioritization of recommendations is presented in Table 5.

Table 5. Prioritization of Improvement Recommendations Based on the Action Priority Matrix

No	Recommendation	Code	Quadran
1	Dedicated Storeman	A	Quick Win
2	Storage centralization	B	Quick Win
3	Daily Inventory Report	E	Quick Win
4	Integrated Material Visibility and Tracking System (Application/Software)	H	Major Project
5	Dashboard Material	I	Major Project
6	Ensure 5S Compliance	J	Major Project
7	Additional Truck	C	Fill-ins
8	Fence & CCTV	D	Fill-ins
9	Box or Skid Package	F	Fill-ins
10	5S Inspection	G	Fill-ins
11	Install OHC (Overhead Crane)	K	Fill-ins

No	Recommendation	Code	Quadran
12	Repacking Material	L	Thankless Task
13	Return of remaining material	M	Thankless Task

Impact-Complexity Analysis

To provide a more comprehensive evaluation of the proposed improvement initiatives, an Impact–Complexity Analysis was conducted on the recommendations categorized as Quick Wins and Major Projects. The impact score was derived from each initiative's expected contribution to improving material availability, accessibility, traceability, and auditability. The complexity score was evaluated based on organizational impact, process changes, infrastructure requirements, implementation dependency, cost, and implementation duration. The assessment was developed through stakeholder discussions and validated by Subject Matter Experts (SMEs). The Impact–Complexity Ratio was then calculated by dividing the Impact Score by the Complexity Score. A higher ratio indicates that an initiative is expected to deliver greater operational benefits relative to the effort and complexity required for implementation.

Table 6. Impact–Complexity Analysis Results

No	Recommendation	Impact Score	Complexity Score	Impact Complexity Ratio
1	Dedicated Storeman	6	1.9	3.23
2	Ensure 5S Compliance	10	3.9	2.59
3	Daily Inventory Report	3	1.6	1.91
4	Storage Centralization	6	3.7	1.62
5	Dashboard Material	3	2.4	1.24
6	Integrated Material Visibility and Tracking System	3	4.6	0.66

The results indicate that Dedicated Storeman achieved the highest Impact–Complexity Ratio (3.23), followed by Ensure 5S Compliance (2.59) and Daily Inventory Reporting (1.91). These initiatives provide the most favorable balance between operational impact and implementation effort. In contrast, the Integrated Material Visibility and Tracking System recorded the lowest ratio due to its higher implementation complexity, although it remains strategically important for achieving long-term material visibility and traceability. Overall, the analysis supports prioritizing Dedicated Storeman, 5S Compliance, and Daily Inventory Reporting as the most practical improvement initiatives for short- to medium-term implementation.

Control Phase

The Control phase was developed to ensure that the proposed improvement initiatives can be implemented in a sustainable manner and continue to support improvements in inventory control and storage management. Based on the dependency among the proposed solutions, an implementation roadmap was developed to guide the deployment sequence and ensure that each initiative supports the next stage of improvement.

Implementation Roadmap

The implementation roadmap begins with the assignment of Dedicated Storeman to establish accountability and improve control over storage activities. Once ownership has been established, Daily Inventory Reporting can be implemented to improve inventory visibility and support better replenishment decisions. The next stage focuses on Storage Centralization and 5S Compliance to improve storage organization, reduce storage fragmentation, and standardize storage practices. Finally, a Material Dashboard and an Integrated Material Visibility and Tracking System are proposed as long-term initiatives to support real-time inventory monitoring and material traceability.

Although the Impact–Complexity Analysis showed that Dedicated Storeman, 5S Compliance, and Daily Inventory Reporting provide the best balance between expected benefits and implementation effort, the implementation roadmap was not determined solely based on the ranking results. The roadmap also considered the dependency among the proposed initiatives and the practical requirements for successful implementation. Therefore, Storage Centralization was placed before 5S Compliance because a more organized and centralized storage environment is needed before 5S practices can be implemented effectively and sustained over time. As a result, the implementation sequence reflects not only the priority of each initiative but also the logical order required to achieve sustainable improvements.

Table 7. The Schedule of Implementation

Project Plan	Nov-26				Dec-26				Feb-27				Mar-27				Apr-27				Feb-28			
	W 1	W 2	W 3	W 4	W 5	W 6	W 7	W 8	W 13	W 14	W 15	W 16	W 17	W 18	W 19	W 20	W 21	W 22	W 23	W 24	W 61	W 62	W 63	W 64
Improve																								
- Quick Wins Project																								
Dedicated Storeman																								
Daily Inventory Report																								
Storage Centralization																								
- Major Projects																								
Ensure 5S Compliance																								
Dashboard Material																								
Integrated Material Visibility and Tracking System																								
Control																								
• Inventory Monitorong																								
KPI: % Material availability, Number of stockout cases, Inventory Accuracy																								
• Monthly 5S Assesment																								
KPI: 5S Audit Score																								
• Management Review Meeting																								

Control Plan

To monitor the effectiveness of the proposed improvements, several key performance indicators (KPIs) were identified. These indicators are intended to measure inventory performance, storage conditions, and the overall effectiveness of inventory control practices.

Table 8. Control Plan

No	KPI	Target	Monitoring Method	Frequency
1	Material Availability (%)	≥ 99%	Dashboard Material & Inventory Report	Weekly
2	Inventory Accuracy (%)	≥ 99%	Cycle Count Verification	Monthly
3	5S Audit Score	≥ 90%	Monthly 5S Assessment	Monthly
4	Number of Outstanding Inventory Issues	0 Critical Issue	Management Review Meeting	Monthly

As shown in Table 7, each proposed improvement is supported by specific monitoring and control mechanisms to ensure long-term performance sustainability. Through periodic monitoring, inventory verification, 5S audits, and management review activities, the organization can maintain the effectiveness of the implemented improvements and prevent the process from returning to its previous condition.

CONCLUSION

This study applied the Lean Six Sigma DMAIC framework to analyze inventory control and storage management issues related to consumable ground support materials in underground mining operations at PT Freeport Indonesia. The findings identified four primary root causes: the absence of a standardized inventory management system, the lack of dedicated personnel and control systems in shadow storage areas, inadequate implementation of storage standards and 5S practices, and limited availability of transportation equipment. These issues collectively reduced inventory visibility, weakened material traceability, and increased the risks of material shortages and inefficient storage utilization.

To address these challenges, thirteen improvement initiatives were initially identified. Using the Action Priority Matrix, six initiatives were selected as priority recommendations and classified as either Quick Wins or Major Projects: Dedicated Storeman, Daily Inventory Reporting, Storage Centralization, 5S Compliance, Material Dashboard, and an Integrated Material Visibility and Tracking System. Subsequent Impact–Complexity Analysis showed that Dedicated Storeman, Daily Inventory Reporting, and 5S Compliance provided the most favorable balance between expected benefits and implementation effort. These findings, together with the interdependencies among the proposed solutions, formed the basis for the implementation roadmap.

From a managerial perspective, different improvement strategies are recommended for each mining area. For the DMLZ Mine, the primary focus should be on simplifying material flow through Storage Centralization and reducing multi-stage storage activities. This approach is expected to reduce unnecessary material handling, improve material accessibility, and minimize inventory accumulation across multiple storage points. For the GBC and KL Mines, the main priorities should be strengthening inventory control and storage governance through Dedicated Storeman, enhanced 5S implementation, and improved inventory visibility. In addition, Storage Centralization should be considered to reduce fragmented storage, improve material traceability and inventory accuracy, and gradually eliminate shadow storage through the implementation of centralized and controlled storage locations. Given the similar operational characteristics of GBC and KL, a standardized inventory control and storage management approach should be applied across both mining areas.

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