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Integrating Lean Six Sigma and Soil Quality Preservation in Topsoil Removal Operations: A Case Study of Indonesian Coal Mining

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Abstract
Topsoil removal is a critical activity in surface coal mining operations because it directly affects operational productivity and the success of post-mining land rehabilitation. This study aimed to identify operational waste within the topsoil removal process, develop improvement strategies to enhance productivity, and evaluate the role of soil quality preservation in supporting sustainable mining practices. The study employed a Lean Six Sigma framework using the DMAIC (Define, Measure, Analyze, Improve, Control) methodology. Value Stream Mapping (VSM), Cycle Time Analysis, Pareto Analysis, and Failure Mode and Effects Analysis (FMEA) were applied to identify process inefficiencies, prioritize critical operational issues, and formulate improvement strategies. The findings revealed that approximately 43.37% of the total operational cycle time consisted of non-value-added activities, with the dominant sources of waste occurring in loading queue time, traffic conflicts at intersections shared with overburden hauling operations, haul road-related travel delays, blasting interruptions, and operator-related delays. The FMEA results further identified loading queue time (RPN = 324), traffic conflicts (RPN = 320), and haul road delays (RPN = 280) as the most critical operational risks. The proposed improvement initiatives were estimated to reduce cycle time by approximately 20% and increase hauling productivity by around 24%. Beyond productivity improvement, this study highlighted the importance of preserving topsoil quality through controlled handling practices and the application of lower-impact equipment to minimize soil compaction and maintain humus integrity. The findings demonstrated that operational efficiency and soil quality preservation could be achieved simultaneously through a systematic Lean Six Sigma approach, contributing to sustainable mining operations and successful post-mining land reclamation.

INTRODUCTION

Topsoil is widely recognized as the most biologically active soil layer, containing high concentrations of organic matter, nutrients, and microorganisms essential for maintaining land productivity and ecological balance (Schlüter et al., 2022). Globally, topsoil plays a critical role in supporting ecosystem services, including water regulation, carbon sequestration, and vegetation growth (Anuo et al., 2024). However, increasing pressure from land-intensive human activities has accelerated topsoil disturbance and removal, particularly in sectors such as open-pit mining, infrastructure development, and large-scale earthworks (Misebo et al., 2022; Hondroudakis et al., 2024). Consequently, topsoil degradation has become a global concern that extends beyond environmental science into the field of sustainable industrial management.

In the mining industry, topsoil removal is an unavoidable operational activity. It represents one of the initial stages of open-pit mining and must be completed before overburden stripping and coal extraction activities can proceed. Due to its position within the mining sequence, topsoil removal directly affects pit readiness, equipment utilization, and overall production schedules. Therefore, mining companies often manage topsoil stripping primarily from a productivity and volume-achievement perspective. Although this operational focus is understandable, it may result in insufficient attention to the long-term impacts of topsoil disturbance on soil quality and land functionality (Bai et al., 2018; Gregory et al., 2015; Larney et al., 2016; Si et al., 2026; Teague & Kreuter, 2020).

A growing body of scientific literature has demonstrated that topsoil removal causes substantial degradation of soil properties. Geissen et al. (2013) found that topsoil stripping resulted in significant losses of soil organic carbon, reaching up to 88–94%, and impaired soil buffering and filtering functions. Importantly, their findings indicated that the recovery of surface vegetation does not necessarily represent the restoration of soil functions (Shokri et al., 2025; Si et al., 2026).

This suggests that topsoil removal generates impacts that may not be immediately visible but can persist within soil systems over extended periods. In addition to chemical and biological degradation, topsoil removal affects soil physical and hydrological properties. Udom et al. (2018) reported that soils subjected to topsoil removal experienced increased bulk density, reduced infiltration capacity, and a significant decline in available water content. Their study showed that useful available water and easily available water could decrease by more than 60% compared with undisturbed soils. These changes create compacted soil structures with lower permeability and greater susceptibility to water stress. In areas with high rainfall intensity, such conditions may increase surface runoff and erosion risks, while during dry periods, they may accelerate soil desiccation and reduce land resilience (Abebaw & Feleke, 2026; Naskar et al., 2025; Zeng et al., 2025).

Long-term studies have further confirmed that the effects of topsoil removal are difficult to reverse. Larney et al. (2016), through a longitudinal study spanning more than two decades, demonstrated that deep topsoil removal produced persistent legacy effects on soil organic carbon and nitrogen levels. Natural recovery of soil quality occurred slowly without targeted intervention, particularly when the depth of removed topsoil exceeded critical thresholds. These findings emphasize that topsoil removal should be considered a major disturbance with long-term consequences rather than merely a temporary operational activity.

In addition to environmental impacts, ineffective topsoil management creates operational and economic challenges for mining activities. Poorly managed topsoil removal may delay subsequent mining stages, reduce equipment productivity due to unstable or compacted ground conditions, and increase the need for rehandling and corrective earthworks. Throughout the mine life cycle, such inefficiencies may contribute to higher operational costs and increased rehabilitation and mine closure expenditures.

As a result, global mining practices have increasingly recognized that early-stage land management decisions significantly influence long-term operational performance and sustainability outcomes. In response to these challenges, international best practices have shifted from a purely volume-oriented approach toward more integrated topsoil management strategies. These practices include selective stripping of biologically active soil layers, careful handling and stockpiling of topsoil, and the application of organic amendments to improve soil resilience. Empirical evidence suggests that even limited early interventions, such as single applications of organic amendments, can generate lasting improvements in soil structure and quality, thereby reducing some negative impacts associated with topsoil removal (Larney et al., 2016).

Despite extensive research on the environmental consequences of topsoil removal, relatively limited attention has been given to the operational performance of topsoil removal activities themselves. Most existing studies focus on post-disturbance soil recovery, whereas inefficiencies during the removal process, such as excessive cycle time, idle time, equipment imbalance, and non-value-added activities, remain insufficiently explored. This research gap highlights the need for a structured and data-driven approach that considers topsoil removal not only as an environmental issue but also as a process performance challenge.

Accordingly, this study positioned topsoil removal within the dual contexts of environmental responsibility and operational excellence. By applying the Lean Six Sigma framework, this research aimed to identify inefficiencies, reduce non-value-added activities, and improve productivity in topsoil removal operations. Previous studies have demonstrated that Lean and Lean Six Sigma approaches have been successfully applied across various industrial sectors to improve operational efficiency and productivity. Several studies have shown that Lean implementation can significantly reduce operational waste and enhance process performance.

However, existing research on Lean applications in mining operations has primarily focused on processing plants, logistics systems, and equipment maintenance activities. Studies investigating Lean implementation in pre-mining operational stages, particularly topsoil removal and overburden stripping activities, remain limited.

At the same time, research on topsoil removal has predominantly focused on environmental and soil science perspectives rather than operational efficiency and productivity analysis. This condition highlights a research gap at the intersection of two research domains: operational efficiency improvement in mining processes and process optimization of topsoil removal activities. Specifically, limited research has examined how Lean Six Sigma methodologies can be applied to identify operational waste and improve productivity in topsoil removal operations.

Therefore, this study aimed to address this gap by applying Lean Six Sigma tools to analyze operational inefficiencies in topsoil removal processes. By integrating Value Stream Mapping (VSM), cycle time analysis, Pareto analysis, and Failure Mode and Effects Analysis (FMEA), this research sought to identify operational waste and propose improvement strategies to enhance productivity in topsoil removal operations.

Although topsoil removal is a routine mining activity, it also has significant environmental implications. Several studies have examined the ecological and soil-related impacts of topsoil removal. Larney et al. (2016) investigated the long-term effects of topsoil removal on soil resilience and found that the removal process significantly reduced soil organic carbon and nutrient content, potentially affecting soil recovery capacity. Similarly, Udom, Omovbude, and Abam (2018) examined the structural and hydraulic effects of topsoil removal on soil properties and found that it significantly reduced soil infiltration capacity and water retention, increasing the risk of soil degradation.

Preserving topsoil quality is essential because topsoil contains most of the organic matter, nutrients, microorganisms, and seed banks required for vegetation establishment during reclamation. Geissen et al. (2013) analyzed the ecological consequences of topsoil removal in nature management systems and found that removing nutrient-rich topsoil significantly reduced soil biological activity and carbon storage capacity. Their findings demonstrated that topsoil functions not only as a physical growth medium but also as a critical component of ecosystem resilience and recovery. Therefore, maintaining topsoil quality during stripping, hauling, and stockpiling activities is an important factor in supporting long-term reclamation success. Other studies have reported similar findings. Lal (2004) emphasized that soil erosion and topsoil removal significantly reduce soil fertility and agricultural productivity. Meanwhile, Blanco-Canqui and Lal (2008) highlighted the importance of soil organic matter in maintaining soil structure and ecological functions.

The urgency of this research is reinforced by the strategic role of the coal mining sector in Indonesia's economy and increasing regulatory demands for sustainable mining practices. With growing awareness of environmental impacts and the need for successful post-mining land rehabilitation, mining companies face the challenge of balancing operational productivity with environmental stewardship. This research is particularly relevant due to the limited application of Lean Six Sigma in pre-mining activities and the need for practical improvement strategies that can be implemented in operational settings. This study aimed to provide practical insights for mining operations seeking to improve productivity while preserving soil quality for successful reclamation.

Although previous studies have provided valuable insights into the environmental consequences of topsoil removal, they have primarily focused on ecological and soil science perspectives rather than operational efficiency. Consequently, limited research has connected environmental understanding of topsoil removal with operational productivity analysis in mining contexts. Based on the operational challenges and research gaps identified above, this study aimed to investigate the application of Lean Six Sigma in improving topsoil removal performance within an open-pit coal mining operation. Specifically, the study sought to identify the dominant sources of operational waste throughout the topsoil removal process, evaluate critical factors contributing to productivity losses, and develop improvement strategies to enhance operational efficiency. Furthermore, this research examined how productivity improvement initiatives could be aligned with soil quality preservation objectives to support successful land reclamation. By integrating operational excellence and environmental considerations, this study contributes to discussions on sustainable mining practices, particularly in pre-mining activities that have received limited attention in previous Lean Six Sigma research.

METHOD

Research Design

This research employed the Lean Six Sigma (LSS) methodology as a structured and data-driven approach to improve topsoil removal productivity in open-pit coal mining operations. Lean Six Sigma was selected because of its ability to identify operational inefficiencies, reduce process variability, and improve process performance in complex, equipment-intensive environments. Considering that topsoil removal involves repetitive earthmoving activities, high dependency on equipment coordination, and sensitivity to cycle time variations, the Lean Six Sigma approach was considered suitable for addressing productivity challenges in this context.

The research was designed using the DMAIC framework (Define, Measure, Analyze, Improve, and Control) with methodological adjustments tailored to topsoil removal operations. In the Define phase, Value Stream Mapping (VSM) was applied to develop an overview of the current operational process by visualizing material and information flows and identifying non-value-added activities. This approach enabled the research problem to be defined based on actual operational conditions.

In the Measure phase, Cycle Time Analysis and Pareto Analysis were applied to evaluate current process performance and identify the dominant sources of productivity loss. Cycle Time Analysis was used to measure the duration of loading, hauling, dumping, and return activities within a complete operational cycle. By breaking down cycle time into individual components, this analysis provided insights into sources of time loss and productivity variation.

Pareto Analysis was subsequently used to categorize and rank operational losses, such as waiting time, equipment downtime, rehandling activities, and haul road-related delays, based on their frequency and contribution to overall productivity losses. The integration of Cycle Time Analysis and Pareto Analysis enabled objective identification of time-based inefficiencies and major operational constraints.

The Analyze phase applied Failure Mode and Effects Analysis (FMEA) to evaluate the root causes of prioritized operational issues. Based on the results of the Measure phase, FMEA was used to identify potential failure modes in the topsoil removal process, assess their impacts on productivity, and determine risk priorities based on severity, occurrence, and detection criteria. This analysis supported the prioritization of improvement efforts toward failure modes with the greatest impact on operational performance.

In the Improve phase, improvement strategies were developed based on FMEA results and classified into corrective and preventive action plans. Corrective actions focused on addressing existing root causes of high-risk failure modes, while preventive actions aimed to minimize recurrence through improved process control, standardized work methods, and enhanced coordination among operational stakeholders. This approach ensured that proposed improvements addressed both current inefficiencies and potential future risks.

The Control phase focused on maintaining improvements achieved throughout the previous phases. Control measures included establishing performance indicators, monitoring cycle time and productivity metrics, and incorporating improvement initiatives into standard operating procedures. Continuous monitoring and evaluation ensured that productivity improvements in topsoil removal operations could be sustained and integrated into daily operational practices.

Overall, this research design provided a systematic framework for improving topsoil removal productivity by integrating process visualization, quantitative measurement, risk-based analysis, and continuous improvement strategies within a modified Lean Six Sigma DMAIC framework.

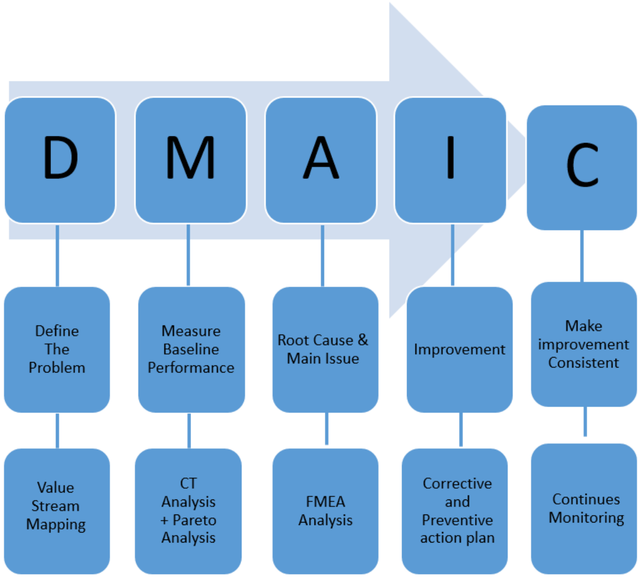

Figure 1. Research Design

RESULTS AND DISCUSSION

Current State Value Stream Mapping (VSM)

To capture the actual operational condition, a current-state Value Stream Map (VSM) is developed based on field observations and operational data. The VSM illustrates the sequence of activities involved in topsoil removal, along with the corresponding material and information flow.

The mapping includes four main operational stages: loading, hauling (loaded), dumping, and return travel. In addition, delays such as waiting time and queuing are explicitly represented in the map to highlight inefficiencies within the process.

By visualizing the process in this manner, the VSM provides a comprehensive overview of how work is performed in the field and serves as a foundation for identifying areas of improvement.

From total average cycle time 32 minutes value added time is 17.8 minutes, and for the non value added type activity recorded for 17.2 minutes. Field observations indicate that the process is highly dependent on coordination between excavators and hauling units. Any delay in one stage directly affects the overall cycle time and productivity.

Cycle Time Analysis

The cycle time analysis not only provides a quantitative breakdown of operational time but also reveals the underlying factors contributing to variability within the topsoil removal process. Based on field observations, variations in travel time, both in loaded and empty conditions, are significantly influenced by several operational and environmental factors.

One of the primary factors affecting travel time is haul road condition. Uneven road surfaces, soft ground conditions, and inadequate maintenance contribute to reduced hauling speed and increased travel duration. In addition, the presence of multiple intersections within the hauling route, particularly those shared with overburden (OB) hauling activities, introduces traffic conflicts that further delay truck movement. These intersections often require trucks to slow down or stop, increasing both loaded and empty travel time. Operational delays are also influenced by human-related factors. Field observations indicate that inefficiencies such as extended break times, including meal and prayer delays, contribute to idle time within the system. In addition, waiting time due to blasting activities further disrupts operational continuity, particularly when hauling units are required to halt operations for safety reasons. These factors introduce variability in cycle time and reduce overall system efficiency.

From the loading perspective, the performance of the loading process is also affected by the physical condition of the loading point. Soft or muddy ground conditions reduce excavator efficiency and increase loading time due to limited maneuverability and reduced digging performance. Conversely, excessively hard material conditions require additional effort during excavation, which also slows down the loading process. Furthermore, the use of top loading methods, as opposed to standard loading configurations, introduces additional challenges. Top loading requires more precise positioning of hauling units and often results in longer loading cycles due to limited visibility and restricted maneuvering space. This condition contributes to inefficiencies in both loading time and truck spotting activities.

Overall, these findings indicate that the variability observed in cycle time is not solely driven by mechanical or equipment-related factors, but also by a combination of road conditions, operational interactions, and human-related inefficiencies. These factors collectively contribute to increased non-value-added time within the topsoil removal process and highlight the need for a more integrated approach to operational improvement.

Based on field observations, the average cycle time is recorded at 32 minutes, with significant variability observed across different cycles with approxemately minimum cycle time at 30 minutes and maximum in 34 minutes. The analysis shows that a considerable portion of the cycle time is consumed by waiting activities, indicating inefficiencies in operational coordination. Furthermore, the breakdown of cycle time reveals that non-value-added activities account for 43.37% of the total cycle time. From a Lean perspective, this indicates the presence of operational waste that negatively affects process efficiency. The results of Cycle Time Analysis provide a quantitative basis for identifying inefficiencies and serve as input for further prioritization using Pareto Analysis.

Pareto Analysis Results: Inefficiencies Loading Operations

The Pareto analysis further reinforces the findings from the cycle time analysis by highlighting the dominant sources of operational inefficiencies. The results indicate that queue time at the loading point remains the most significant contributor to total operational delay. This condition is closely associated with several underlying factors observed in the field. Firstly, the bunching between hauling units while waiting excavator capacity leads to excessive queuing at loading points. Secondly, variations in travel time caused by road conditions and traffic conflicts result in inconsistent truck arrival patterns, further contributing to queue formation.

In addition, delays caused by operational interruptions, such as blasting activities and extended break periods, reduce system availability and increase idle time. These interruptions disrupt the flow of operations and create accumulation effects, where delays in one part of the system propagate to other stages. The Pareto analysis also highlights that inefficiencies in loading operations, particularly those influenced by poor ground conditions and the use of top loading methods, contribute to extended cycle time. Although these factors may appear secondary, their cumulative impact significantly affects overall process performance. These findings suggest that the dominant operational issues are not isolated but are interconnected within the system. Therefore, addressing these issues requires a comprehensive approach that considers both technical and operational factors.

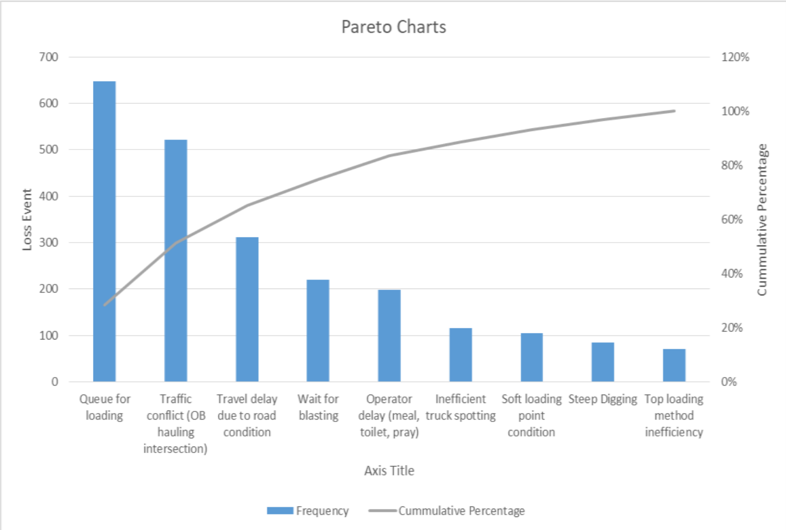

Figure 2. Pareto Chart of Loss Event Topsoil Removal PT.BBB

FMEA Results: Queue Problems, Overburden Hauling, and Poor Haul Road

Based on the Pareto analysis results, a Failure Mode and Effects Analysis (FMEA) is conducted to further evaluate the critical operational risks within the topsoil removal process. The frequency of events identified in the Pareto chart is used as a primary reference in determining the occurrence rating (O), ensuring that the analysis reflects actual field conditions.

Each failure mode is assessed based on its impact on productivity (severity), its frequency of occurrence, and the ability of the system to detect or prevent the issue. This approach allows for a more objective prioritization of operational problems and ensures that improvement efforts are directed toward the most critical areas.

Table 1. FMEA Analysis Topsoil Production PT.BBB

No	Failure Mode	Event (Pareto)	Effect on Operation	Root Cause	S	O	D	RPN	Risk Level
1	Truck queue at loading	648	High waiting time, increased cycle time	Fleet imbalance, irregular truck arrival, Bunching Start	9	9	4	**324**	HIGH
2	Traffic conflict at OB intersection	521	Hauling interruption, reduced speed	Shared haul road	8	8	5	**320**	HIGH
3	Travel delay due to road condition	312	Increased hauling time	Poor road condition, muddy surface	8	7	5	**280**	HIGH
4	Wait for blasting	220	Operation stoppage	Loading or hauling area in blasting radius	7	6	6	**252**	HIGH
5	Operator delay (meal, toilet, pray)	198	Idle time, reduced productivity	Weak time discipline, lack of monitoring	6	6	5	**180**	MEDIUM
6	Inefficient truck spotting	116	Increased loading time	Poor loading point condition, operator skils	7	5	5	**175**	MEDIUM
7	Soft loading point condition	105	Slow loading process	Poor ground condition & preparation	6	5	6	**180**	MEDIUM
8	Steep digging condition	84	Reduced digging efficiency	Unfavorable digging angle	6	4	6	**144**	LOW
9	Top loading inefficiency	70	Longer loading cycle	Limited maneuvering space	5	4	6	**120**	LOW

Queue at loading points has the highest Risk Priority Number (RPN) of 324, making it the most critical issue within the topsoil removal process. This result indicates that excessive waiting time during loading not only occurs frequently but also has a substantial impact on cycle time and overall equipment productivity. The high occurrence of this issue suggests that operational imbalance, particularly between truck availability and loading capacity, remains a recurring challenge in daily activities.

The second highest risk is associated with traffic conflicts at intersections shared with overburden hauling activities, with an RPN value of 320. This finding highlights that interactions between different hauling operations create interruptions in traffic flow, contributing to longer travel times and unstable cycle performance. In practice, trucks often experience delays due to overlapping routes and limited traffic control at operational intersections.

Another significant contributor to inefficiency is travel delay caused by poor haul road conditions, which records an RPN value of 280. Field observations indicate that uneven road surfaces, muddy conditions, and inadequate maintenance reduce hauling speed and increase variability in travel time. Although hauling activities are generally considered value-adding processes, prolonged travel duration may indicate opportunities for operational improvement.

Delays related to blasting activities also show relatively high risk levels, emphasizing the importance of coordination between production and blasting schedules. Meanwhile, medium-risk issues such as operator-related delays, inefficient truck positioning, and unfavorable loading point conditions demonstrate that human factors and operational preparation also influence process efficiency, although to a lesser extent.

Overall, the FMEA findings suggest that the main sources of inefficiency in the topsoil removal process are closely related to operational flow and coordination rather than equipment performance alone. High-risk issues are primarily concentrated around loading management, hauling movement, and operational interruptions.

This indicates that improving productivity may not necessarily require additional equipment capacity, but rather better synchronization between operational activities, improved traffic management, and stronger control over process variability. Therefore, improvement efforts should focus on reducing waiting time, optimizing hauling flow, and strengthening preventive operational controls before work begins.

These findings provide a basis for the Improve phase, where corrective actions and preventive measures are developed to address the root causes of high-priority failure modes identified in the analysis.

Improvement Strategy

The Improve phase focuses on developing targeted solutions to address the critical failure modes identified in the FMEA. Rather than proposing generic improvements, this study prioritizes actions based on the highest Risk Priority Numbers (RPN), ensuring that improvement efforts are directed toward issues with the greatest impact on operational performance.

The proposed solutions are derived from field observations and operational insights, combining corrective actions to address existing inefficiencies and preventive actions to ensure long-term sustainability. The improvements are designed to reduce non-value-added time, stabilize cycle time, and enhance overall productivity in the topsoil removal process.

Table 2. Corrective and Preventive Action Plan

No	Failure Mode	Corrective Action (Short-Term)	Preventive Action (Long-Term)	Expected Impact
1	Truck queue at loading	Rebalance fleet (truck–excavator ratio), dispatch adjustment	Fleet management start SOP, Implement real-time dispatch system & queue monitoring.	Reduce waiting time significantly
2	Traffic conflict (OB intersection)	Assign traffic controller at intersections	Design dedicated hauling lanes / traffic SOP	Reduce hauling interruption
3	Road condition delay	Immediate road grading & maintenance	Scheduled road maintenance plan + road quality KPI	Increase hauling speed
4	Blasting delay	Improve coordination between blasting & hauling	Integrated blasting–production scheduling system	Reduce stoppage time
5	Operator delay	Enforce break time discipline	Monitoring system & shift control SOP	Reduce idle time
6	Truck spotting inefficiency	Briefing for operators, improve communication	Standardized spotting procedure (SOP)	Reduce loading delay
7	Soft loading point	Ground preparation before operation	Soft Hauling SOP, pair more dozer to support digging activity	Improve excavator efficiency
8	Steep digging	Adjust digging position	Planning digging sequence	Improve digging cycle
9	Top loading inefficiency	Optimize truck positioning	Minimize use of top loading method	Reduce loading time

In addition to corrective actions, this study proposes the implementation of preventive Standard Operating Procedures (SOPs) supported by structured checklists. These SOPs are designed to be executed before the start of each operational shift to ensure that critical risk factors are identified and mitigated proactively. By implementing a preventive approach, operational variability can be reduced, and process stability can be improved in a sustainable manner.

The proposed improvement strategies focus on enhancing operational flow and reducing variability within the system. The reduction of queue time is achieved by improving fleet balance and dispatch coordination, ensuring a more consistent arrival pattern of hauling units. Improvements in traffic management and haul road conditions are expected to stabilize hauling time, which represents a significant portion of the total cycle time. In addition, better coordination between blasting and hauling operations aims to reduce unexpected operational interruptions. From a loading perspective, improving ground conditions and standardizing truck positioning procedures contribute to more efficient loading operations and reduced cycle variability.

The preventive improvement strategy is developed based on the root causes identified in the FMEA. Instead of addressing issues after they occur, the approach focuses on controlling critical operational factors before the process begins. This includes ensuring proper equipment allocation, road condition readiness, traffic management, and operational coordination. The use of a structured checklist system allows supervisors and operators to verify key operational conditions before execution, reducing the likelihood of delays and inefficiencies during operation.

The implementation of this checklist-based SOP ensures that critical operational risks are addressed before the start of each shift. By verifying key factors such as fleet balance, road condition, traffic flow, and loading point readiness, the likelihood of operational disruptions can be significantly reduced. This preventive approach aligns with Lean principles by eliminating potential waste before it occurs, particularly waiting time and unnecessary delays. In addition, the SOP enhances operational discipline and standardization, which are essential for sustaining process improvements.

The comparison between the current and improved operational conditions shows a significant reduction in cycle time from 32 minutes to 25.6 minutes, representing an improvement of approximately 20%. The most substantial improvement is observed in queue time at the loading point, which is reduced by more than 50%, indicating the effectiveness of improvements in fleet coordination and dispatch management. As a result, the number of trips per hour increases from 1.88 to 2.34, leading to an estimated productivity improvement of approximately 24%. These results demonstrate that reducing non-value-added activities, particularly waiting time, has a direct and significant impact on overall operational performance.

The application of preventive SOPs is expected to directly reduce the occurrence of high-risk failure modes identified in the FMEA, particularly those related to queue formation, traffic conflict, and operational delays. By controlling these factors at the beginning of the operation, cycle time variability can be minimized, leading to improved productivity and operational stability.

Soil Preservation Discussion

Beyond operational efficiency, this study draws attention to a concern that is often underappreciated in mining contexts: the preservation of topsoil quality for use as a planting medium in post-mining land rehabilitation. Topsoil is far more than an inert layer of ground material it is a biologically active medium rich in organic matter, including humus, that sustains soil fertility, regulates water retention, and supports plant growth. For this reason, the way topsoil is handled during removal cannot be evaluated on productivity metrics alone; the integrity of its physical and biological structure must be considered with equal seriousness.

Figure 3. Organic Matter in Topsoil

A well-established body of literature affirms that the uppermost soil horizon harbors the greatest concentration of organic matter and microbial activity both of which are foundational to ecosystem recovery following land disturbance. Lal (2004) demonstrated that improper removal and handling of topsoil leads to substantial losses in soil organic carbon, with cascading effects on long-term soil fertility. Building on this, Blanco-Canqui and Lal (2008) showed that structural degradation resulting from excessive compaction impairs two processes critical to vegetation establishment: water infiltration and root development.

In the context of active mining operations, heavy equipment traffic represents one of the most persistent and damaging sources of soil compaction. Each pass of large-scale machinery exerts considerable ground pressure, progressively reducing the pore space that roots and soil organisms depend on. As Hamza and Anderson (2005) explained, compaction-induced reductions in oxygen availability and root penetration capacity do not merely inconvenience reclamation efforts they can fundamentally undermine the success of vegetation recovery in rehabilitated areas.

One practical response to this challenge, observed directly in the study area, involves prioritizing the use of smaller-sized equipment during topsoil removal operations. The rationale is straightforward: lighter machines exert lower ground pressure, which translates into meaningfully reduced compaction risk and better preservation of the humus layer's structural integrity. While this may appear to be a minor operational adjustment, its implications for soil quality and therefore for the long-term viability of reclaimed land are significant.

This field-based practice finds strong support in the scientific literature. Spoor et al. (2003) provided empirical evidence that lighter machinery produces substantially less soil compaction than heavier alternatives operating under comparable conditions. Botta et al. (2006) further identified axle load and equipment size as key determinants of soil deformation, reinforcing the argument that equipment selection is not merely a logistical consideration but an ecological one as well.

An additional and often overlooked advantage of smaller equipment is the degree of precision it affords during excavation. Because topsoil and subsoil differ dramatically in their nutrient content and biological activity, the inadvertent mixing of these two layers during removal can significantly diminish the rehabilitative value of the recovered material. Smaller equipment enables more controlled and selective extraction, helping to maintain the distinction between soil horizons and preserve the nutrient-dense upper layer that reclamation success depends upon.

It must be acknowledged, however, that the use of smaller equipment is not without operational consequences. Reduced machine capacity naturally limits the volume of material that can be moved within a given timeframe, and without careful planning, this constraint can translate into lower production rates. This tension between soil-preserving practices and operational throughput is a genuine challenge that warrants serious consideration rather than dismissal.

This is precisely where the Lean Six Sigma analysis presented in this study offers a meaningful contribution. Rather than accepting reduced productivity as an inevitable cost of responsible soil handling, the findings demonstrate that non-value-added activities particularly waiting time, process misalignment, and coordination inefficiencies can be substantially reduced to offset the throughput limitations associated with smaller equipment. In other words, the system as a whole can be made more efficient even when individual machine capacity is constrained.

This reframing is central to the argument this study advances: productivity and soil preservation need not be treated as competing priorities. When operational management is sufficiently optimized, both objectives can be pursued simultaneously and the assumption that one must be sacrificed for the other reflects a failure of systems thinking rather than an inherent trade-off.

The Lean Six Sigma findings lend direct empirical weight to this position. Reductions in queue time, improvements in equipment traffic flow, and optimization of cycle time collectively produce a more responsive and efficient operational system one that enables better equipment utilization without intensifying the mechanical pressure exerted on the soil. The efficiency gains, in other words, are achieved through smarter coordination rather than heavier machinery.

Viewed through a Lean lens, this alignment is not coincidental. Soil compaction and the reclamation failures it precipitates represent a form of systemic waste one that manifests not only as environmental cost but as downstream operational burden in the form of additional rehabilitation expenditure and extended recovery timelines. Protecting topsoil quality from the outset is therefore consistent with the core Lean principle of eliminating waste at its source, before it has the opportunity to propagate through the broader mining lifecycle.

Importance of Soil Quality in Reclamation Succes Topsoil removal in mining is not merely a preparatory activity but a critical step that determines the success of post-mining land rehabilitation. The upper soil layer contains humus and organic matter that are essential for plant growth, water retention, and soil structure. Studies by Lal (2004) and Hamza and Anderson (2005) show that damage to soil structure due to compaction or improper handling significantly reduces soil fertility and limits vegetation growth.

Therefore, preserving topsoil quality during removal is essential to ensure that it can function effectively as a planting medium during reclamation. Well-preserved topsoil increases the success rate of revegetation, while degraded soil leads to poor plant growth and additional rehabilitation effort.

From a value chain perspective, topsoil can be viewed as a resource that re-enters the system during the reclamation phase. According to Porter (1985), value is created not only during production but also through supporting and downstream activities. In mining, land rehabilitation represents a form of return management, where disturbed land is restored using preserved topsoil.

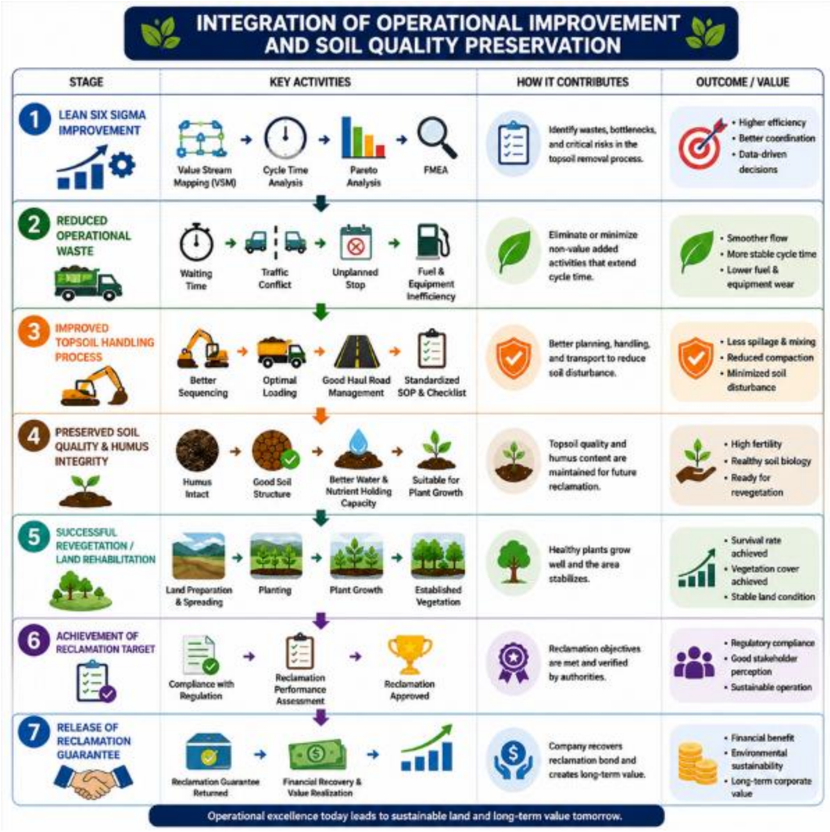

Figure 4. Relationship Between Lean Improvement, Soil Preservation, and Reclamation Value Creation

The quality of topsoil directly affects reclamation outcomes. Successful revegetation, supported by intact humus, becomes a key indicator of rehabilitation performance. This has significant financial implications, as mining companies are required to provide reclamation guarantees before operations begin. The release of these guarantees depends on the success of land rehabilitation, including vegetation growth.

Therefore, maintaining topsoil quality contributes not only to environmental sustainability but also to economic value. By ensuring that topsoil remains suitable for reuse, companies can improve reclamation success rates and recover reclamation guarantees. In this context, topsoil removal becomes a value-adding activity within the mining value chain, aligning operational practices with long-term environmental and financial outcomes.

CONCLUSION

This study demonstrated that operational inefficiencies in topsoil removal activities could be systematically identified and improved through the application of Lean Six Sigma. The findings revealed that a significant portion of the topsoil removal process consisted of non-value-added activities, with approximately 17.2 minutes of the 32-minute average cycle time categorized as operational waste. The dominant sources of waste included excessive queue time at loading points, traffic conflicts at intersections shared with overburden hauling activities, travel delays caused by poor haul road conditions, blasting-related interruptions, and operator-related delays. These inefficiencies contributed to process variability, reduced equipment utilization, and lower achievement of production targets. To address these issues, the study proposed a combination of corrective and preventive improvement strategies. Corrective actions focused on improving fleet balancing, optimizing dispatch coordination, strengthening haul road maintenance practices, enhancing traffic management, and improving synchronization between blasting and production activities. Preventive improvements were also introduced through standardized operational procedures supported by pre-shift checklists, enabling critical operational risks to be identified and controlled before disrupting the process. This approach shifted operational management from a reactive system toward a more proactive and sustainable control mechanism.

The proposed improvements were expected to generate significant operational benefits. The analysis indicated that total cycle time could be reduced from 32 minutes to approximately 25.6 minutes, representing an improvement of around 20%. Furthermore, reductions in waiting time and process variability were estimated to increase truck productivity from 1.88 trips per hour to 2.34 trips per hour, resulting in an overall productivity improvement of approximately 24%. These findings suggested that substantial performance improvements could be achieved without increasing equipment capacity but rather through enhanced operational flow, coordination, and process control. Beyond productivity improvements, this study highlighted the strategic importance of preserving topsoil quality throughout the removal process. The findings emphasized that topsoil should not be considered merely as material to be stripped and transported but as a valuable resource required for successful post-mining land rehabilitation. The use of smaller equipment and controlled topsoil handling practices helped minimize soil compaction, preserve humus integrity, and maintain the biological and physical properties required for revegetation. By preserving topsoil quality, the company could improve the likelihood of successful reclamation outcomes, support long-term environmental sustainability, and enhance its ability to recover reclamation guarantees. From this perspective, topsoil removal represented not only an operational activity but also a value-creating process that connected productivity improvement, environmental stewardship, and long-term business value.

The findings of this study demonstrated that productivity improvement and soil quality preservation should not be considered competing objectives. Through a Lean Six Sigma approach, mining operations could simultaneously improve operational performance, maintain topsoil integrity, and strengthen the long-term success of land rehabilitation programs, thereby creating both operational and environmental value.

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