

DEVELOPMENT OF LEAN MATURITY IN AN EARTHMOVING MINING PROJECT

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ABSTRACT

Earthmoving projects in mining face persistent challenges to production reliability due to high operational variability, changing constraints, extreme weather conditions, and flow instability. While Lean thinking has demonstrated benefits in other industries, its adoption in mining remains limited and insufficiently documented. This article investigates how a maturity model facilitates the adoption of Lean Construction (LC) while explicitly integrating Operations Science principles into a tailings dam raising project at the Alparamar Mining Unit in Junin, Perú.

The research follows a case study approach and applies a structured five-stage method: (1) defining the adoption challenge and target maturity; (2) diagnosing the current state using the MMDPLC maturity model; (3) establishing realistic evolution targets for the production system; (4) experimenting to achieve the target condition through iterative and structured Kaizen events and flow-centric diagnostics; and (5) reassessing the achieved maturity using the same instrument. After 35 weeks of implementation, most maturity components reached Level 2 (Formal), supported by improved flow stability, clearer value identification, and a systematic reduction in waste. The study provides empirical evidence that maturity models translate operations science principles into operational routines in complex and highly variable mining environments and motivates replication and evaluation in other types of mining projects.

KEYWORDS

Lean construction, maturity model, kaizen, design science, production.

INTRODUCTION

Latin America possesses significant mining potential and strategic importance in the global supply of raw materials. In Peru, mining accounted for 66% of the total value of exports in 2025 (Ministry of Energy and Mines (MINEM), 2025), solidifying its position as a key pillar of the economy. However, this prominence has not been matched by a corresponding development in

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advanced production management practices, highlighting the need for approaches focused on efficiency and waste reduction (Rosas et al., 2011; ADEN Business School, 2026).

Increasing productivity is one of the main challenges for developing countries, as it explains a large part of the differences in per capita Gross Domestic Product (McKinsey, 2013). In this context, Lean production emerges as a management approach aimed at maximizing value by eliminating waste and reducing variability, principles derived from the Toyota Production System (Womack et al., 1990; Womack & Jones, 1996; Shah & Ward, 2007).

In the construction sector, Lean Construction (LC) has gained relevance due to its results in improving productivity performance. However, the literature reports diverse implementation strategies, highlighting the absence of a single path (Cano, 2019). In this context, Maturity Models (MM) have been proposed as tools to diagnose the state of Lean adoption and identify opportunities for improvement (Cano, 2020). Ronceros (2023) conducted a detailed study of the MM available in the literature and the relevance of their use depending on the stage of a project. This study identified 10 MM, some of which are solely focused on staff interviews, others on Lean Construction principles, others on cultural behaviors associated with tools, others specifically on the Last Planner System (LPS), and others on LPS, IPD, and Lean culture. This article utilizes the Lean Construction Maturity Model for the Development of Principles (MMDPLC), which allows for the evaluation of Lean-related behaviors and the generation of agile diagnoses during project execution. Furthermore, the method proposed by Ronceros et al. (2024), based on structured Kaizen events, is adopted as a mechanism to facilitate the progressive implementation of LC in the highly variable mining sector. This approach makes a significant contribution to the literature, distinguishing itself from other applications in familiar and commonly studied environments such as urban building construction. This article continues the line of research initiated by Ronceros (2023) by utilizing his generic five-stage method and employing the MMDPLC as a diagnostic tool in an environment characterized by high variability due to the extreme climatic conditions and complex geography of the mining project. This differs from previous research, such as that by Ronceros et al. (2025) and Perez et al. (2021).

This work aims to analyze how a Lean maturity model can facilitate the adoption of Lean practices in an earthmoving project for the raising of a tailings dam in mining, through the application of a structured implementation method in a highly variable environment. This is due to the extreme geographical conditions of the Alparamarca Mining Unit in the Peruvian Andes. In this context, the following research question arises:

How does a maturity model facilitate the adoption of Lean practices in earthmoving projects in mining?

LITERATURE REVIEW

While Lean philosophy has been widely applied in manufacturing and healthcare (Ballard, 2000; Ballard & Howell, 1994; Koskela, 1992), its adoption in construction and mining has been slow and fragmented (Ballard, 2005; De Valence, 2005; Castillo et al., 2015). The mining literature reports theoretical applications and case studies in specific operations and projects (Dunstan et al., 2006; Klippel et al., 2008a; Klippel et al., 2008b), but studies documenting systematic implementations in mining development projects, particularly tailings management projects, are scarce (Loow, 2015).

Although Lean principles are transversal to any industry (Yingling et al., 2000; Dunstan et al., 2006) and the concept of waste is directly applicable to mining (Wijaya et al., 2009), some fundamental principles emerge that allow for the practical application of Lean principles. This is Operations Science (OS), which uses data, models, and principles to optimize workflows and resource use. In practical terms, OS involves shifting the view of a project from a schedule of

tasks to be executed over time to a production system focused on managing production flows, cycle times, variability, identifying bottlenecks, and resource management.

Castillo et al. (2015) mention that there are significant limitations in applying Lean production in the mining industry and, therefore, major challenges to overcome. They also mention the need to bridge the gap between the theoretical application of Lean thinking and its practical implementation. For this reason, initiatives exist to study the impact of implementing lean methodologies in projects with highly variable mining development environments, contributing knowledge that promotes the use of this type of thinking in future projects.

In this sense, Management Models (MM) have been proposed as tools that allow for diagnosing the current state of lean adoption and defining evolutionary improvement trajectories (Perez et al., 2021). However, diagnosis alone is insufficient if it is not complemented by a method that allows for transitioning from the current condition to a desired or target condition.

Thus, Ronceros (2024) propose a method based on structured Kaizen events to facilitate the development of lean maturity in the production management of construction projects, which can be integrated with different MM. This approach is particularly relevant in Peruvian mining projects, characterized by high complexity, interdependence of activities, extreme geographical conditions, and high operational variability (Izquierdo & Arbulu, 2008).

In this context, based on the work of Castillo et al. (2014) and Loow (2015), a gap exists between the theoretical foundations of Lean thinking and its practical application in earthmoving mining projects. In response to this gap, this article analyzes the impact of the progressive adoption of Lean Construction, guided by a Maturity Model (MM) and Ronceros (2023) five-stage composite generic method. The principles of Operations Science were used in operational decisions to manage construction processes, aiming to identify bottlenecks, pinpoint the constraints that generate the greatest variability, and optimize the flow by adjusting work cycles in activities with the greatest impact, such as material handling.

METHODOLOGY

This study adopts a mixed-methods (qualitative-quantitative) applied approach, using a case study in a real mining project. The methodological design corresponds to an intervention-type research study, since the authors actively participated in the design, implementation, and monitoring of Lean Construction practices in the production system of the work faces, as evidenced in Table 1 and Table 2 of the results section.

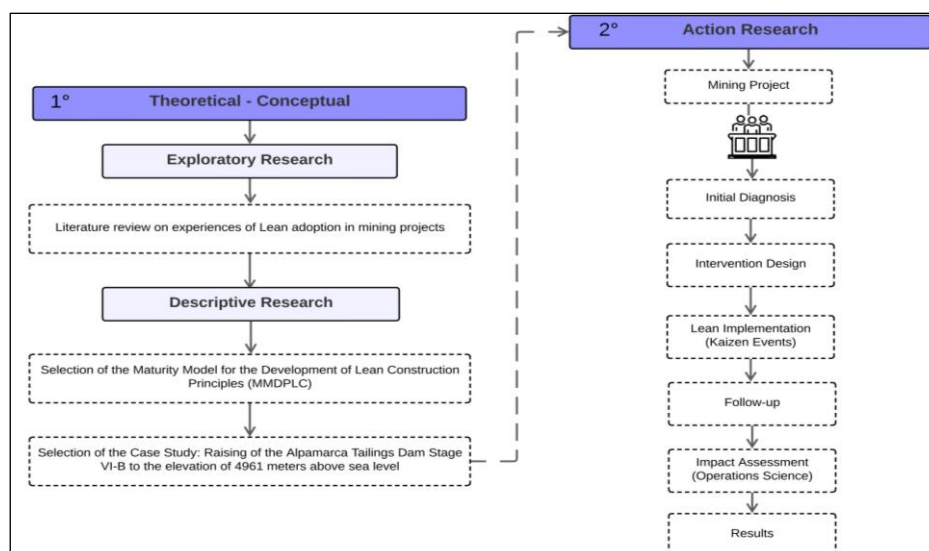


Figure 1: Research method framework.

The methodology is summarized in Figure 1. The first stage involved a literature review to select the most appropriate MM. In this study, the Maturity Model for the Development of Lean Construction Principles (MMDPLC) was chosen due to its focus on behaviors aligned with LC. The model defines six maturity levels (0–5), ranging from the absence of Lean practices (Level 0), through initial adoption (Level 1) and local standardization (Level 2), formalization (Level 3), to institutionalization (Level 4) and consolidation as an organizational culture (Level 5).

A case study was developed in a mining earthmoving project. By adopting the principles of operations science (OS), production flows were mapped and cycle times were measured for the preparation and placement of material for the tailings dam layers. This information facilitated decision-making in the field as part of the action research. Although the results are not generalizable, they provide transferable learning.

CASE STUDY

This case study corresponds to the Alparamarca Mining Unit project, a subsidiary of Volcan Compañía Minera S.A.A. The project is the Alparamarca Tailings Dam Raising – Stage VI-B, at an elevation of 4691 meters above sea level (m.a.s.l.), developed to guarantee the operational continuity of the Alparamarca Concentrator Plant by increasing the tailings storage capacity. At the start of the project, the dam was operational at Stage VI-A (elevation 4689.80 m.a.s.l.), making its raising necessary to ensure the continuity of the metallurgical process, extend the tailings dam's lifespan, and comply with established hydraulic and geotechnical safety standards.

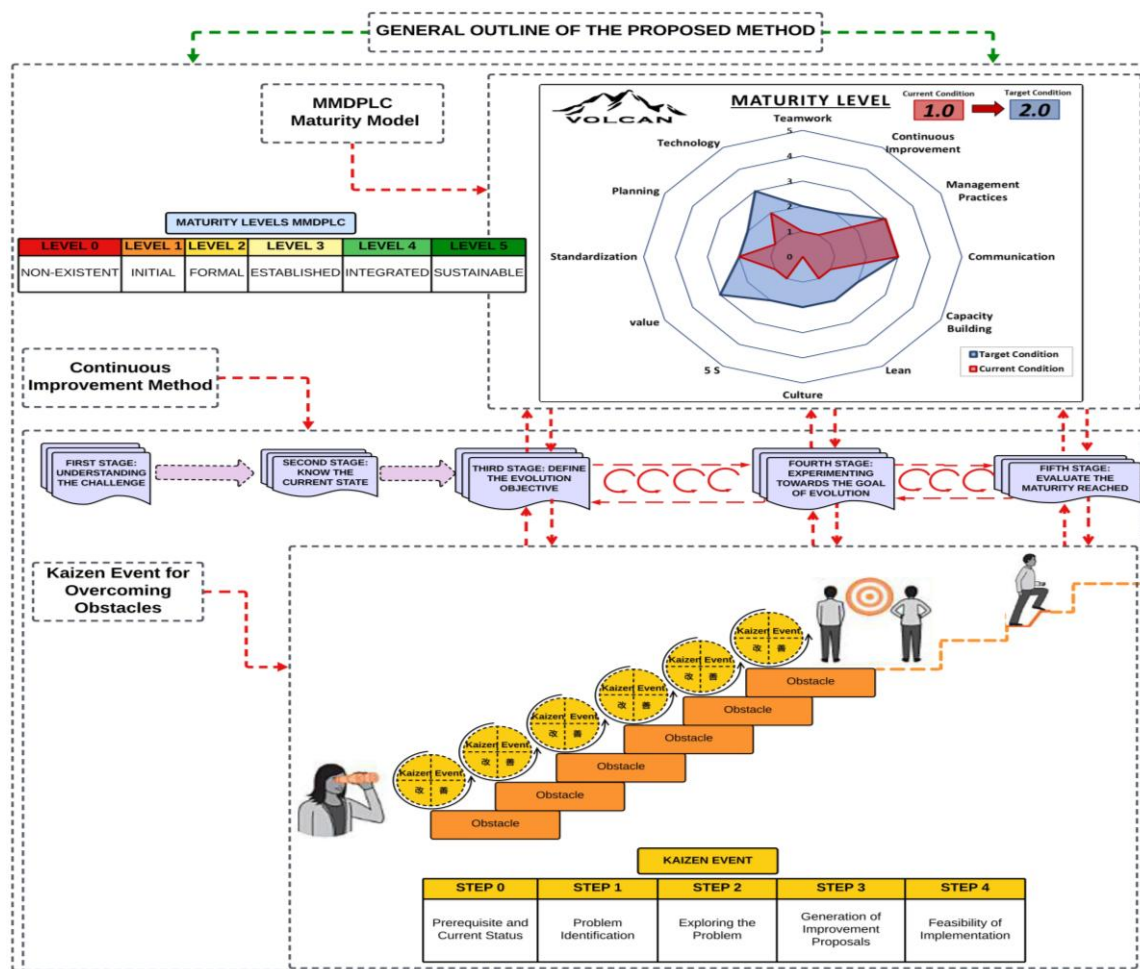


Figure 2: Applied method framework (Adapted from Ronceros et al., 2025).

The project began on June 5, 2025, and includes three components: 1) Foundation Improvement, 2) Raising the Dam to an elevation of 4691 masl and waterproofing upstream, and 3) Hydraulic stabilization works. These activities were carried out at an operating mining unit, under the variable climatic conditions typical of the high Andean region. This increased the complexity and variability of the production system, making the analysis of Lean Construction adoption, supported by a maturity model and the principles of Operations Science, particularly relevant.

The structured method used for the adoption of Lean Construction in this article is a continuation of the research by Ronceros et al. (2025), but within the context of a mining project. The diagnostic tool for maturity is the MMDPLC (Soto, 2016), and the focus is on facilitating the development of Lean maturity for its progressive adoption in the production management of the tailings dam raise. Figure 2 shows the general scheme of the method used, adapted from the research by Ronceros et al. (2025) for the context of an earthmoving project. This is because the first component, foundation improvement, was already underway. Experiences of implementing during project execution were reviewed in the literature, this is based on what was suggested by Mossman (2018), with the framework of implementation during project execution.

FIRST STAGE: UNDERSTANDING THE CHALLENGE

In this case, the proposed challenge is the adoption of LC to manage the production system of the Tailings Storage Facility (TSF) Raise Project – Stage VI-B (Recrecimiento de la Relavera Etapa VI-B). The scope of this adoption aims to ensure that the components of the MMDPLC maturity model reach at least Level 2 (Formal). That is, all MMDPLC components must achieve at least Level 1 (Initial) within the project's production system, and those components specifically oriented to production management must reach Level 2 (Formal). This constitutes the guiding direction for the present case study.

SECOND STAGE: UNDERSTANDING THE CURRENT STATE

The project's technical management operates in a predominantly traditional manner, with a conventional organizational structure and only limited traces of LC knowledge or application. Reporting to Volcan S.A.A. corporate management is conducted using lookahead-type formats, along with a pseudo-analysis of constraints and a reactive identification of causes of non-compliance. This assessment is supported by the application of the MMDPLC evaluation instrument, where the current-state rating is presented in Figure 3.

THIRD STAGE: DEFINING THE EVOLUTION GOAL

The third stage defines the Lean maturity evolution objective based on the MMDPLC diagnosis, establishing realistic goals according to the team's capabilities, the operational context, and project constraints.

Gaps were identified in collaborative planning, standardization, constraint management, and value identification. In the field, cycle times were not controlled, nor were minimum transport targets per dump truck defined, resulting in high variability in production. This lack of control translated into operational inefficiencies, evidenced by waiting times during loading and unloading, as well as unproductive periods during material transport, affecting the flow of the production system.

FOURTH STAGE: EXPERIMENTING TOWARDS THE TARGET CONDITION

For the Alparmarca Tailings Dam Expansion Project – Stage VI-B, the experimentation stage began by prioritizing the MMDPLC maturity approach corresponding to Value Identification (see Figure 3). This decision was based on the fact that this dimension is a key enabling element for stabilizing the production system, reducing operational variability, and creating the

necessary conditions for the progressive and sustainable adoption of more advanced Lean practices in later stages of the project.

In this context, the experimentation was explicitly based on the principles of Operations Science, understood as the analytical framework that allows for the design, analysis, and improvement of complex production systems characterized by high interdependencies and high variability, typical of earthmoving mining projects. Integrating this approach allowed for addressing the project's production system, prioritizing the optimization of the overall flow over isolated local improvements.

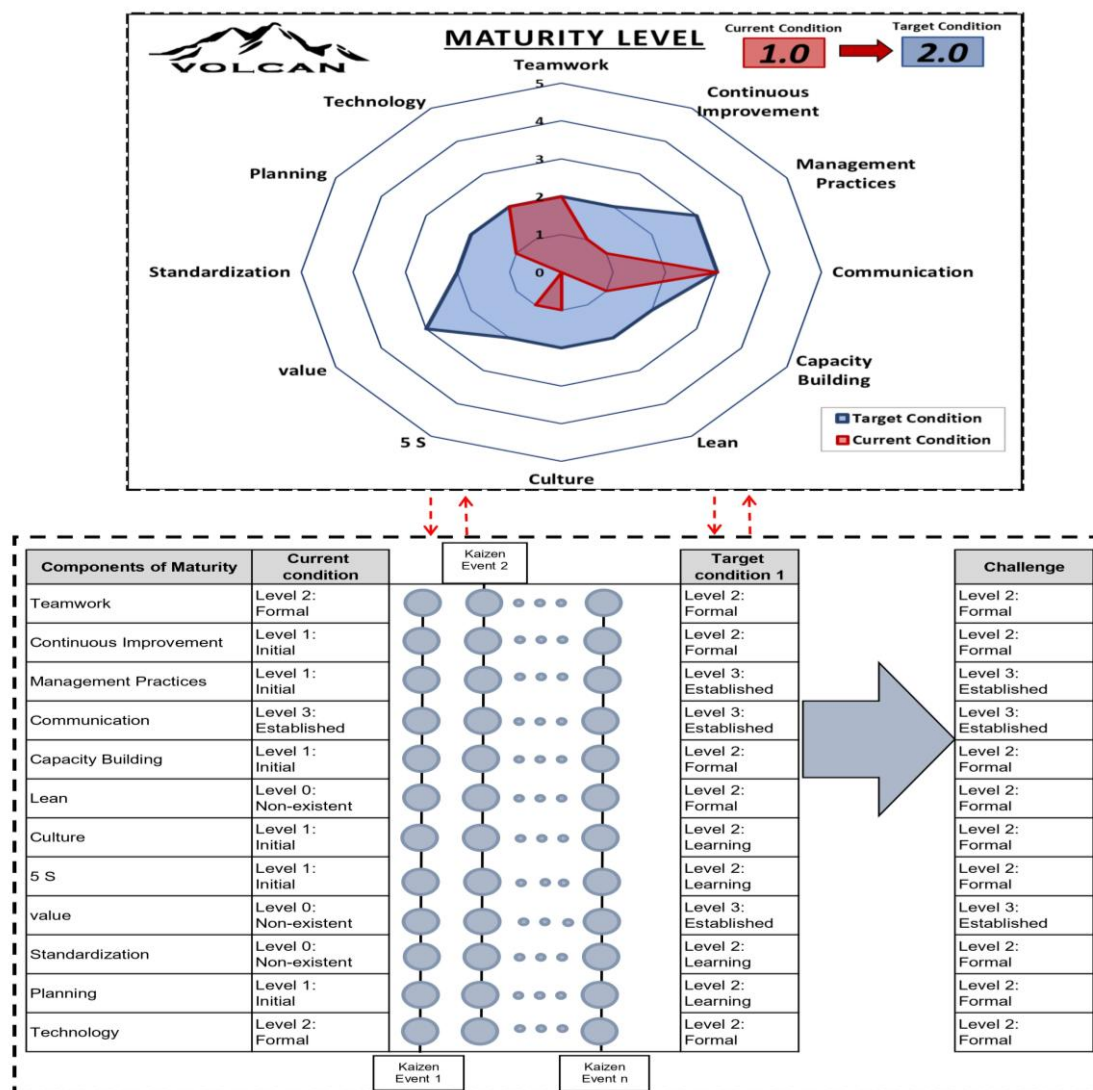


Figure 3: Improvement opportunities within the MMDPLC (Adapted from Ronceros et al., 2025).

The experimentation was developed through iterative learning cycles, structured around Kaizen events, which facilitated the transition from the current state to the target state defined in the previous stage of the method. These cycles were executed by progressively applying the following steps: (1) mapping the workflow to understand the sequence of activities, their interdependencies, and the sources of variability affecting the system's stability; (2) identifying value-adding activities from the production system's perspective, differentiating them from those that do not directly contribute to achieving the production objective; (3) identifying the system's bottleneck, considering the physical, operational, and organizational constraints that

limited overall production capacity; and (4) systematically identifying and eliminating waste, such as waiting, rework, overprocessing, and unnecessary work, aligned with Lean principles.

Figure 4 presents an example of the development of a Kaizen event applied during this stage, which demonstrated the evolution of practices associated with the Value Identification component, achieving characteristics consistent with a Level 3 rating in the maturity model.

This same experimental approach was progressively replicated in the different components of the MMDPLC throughout the 35 weeks of project implementation, allowing for the consolidation of operational learning, strengthening of production management routines, and structured progress in the development of Lean maturity for the production system of the Alparmarca Tailings Dam Raising Project – Stage VI-B.

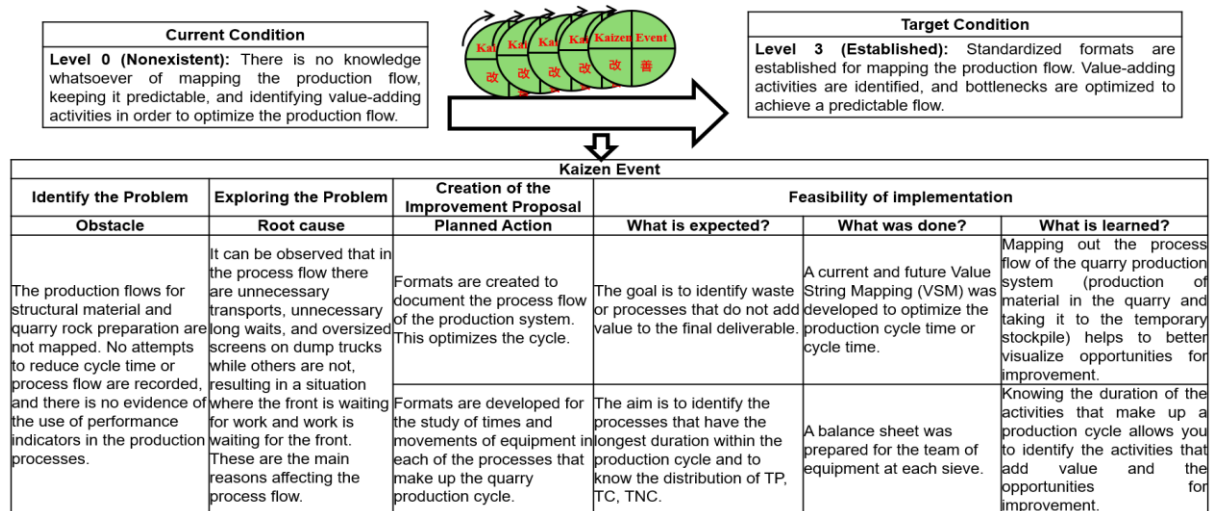


Figure 4: Kaizen event development (Adapted from Ronceros et al., 2025).

FOURTH STAGE: EXPERIMENTING TOWARDS THE TARGET CONDITION

The fifth stage assesses the maturity achieved in production management after 35 weeks of intervention with the MMDPLC, using the same initial instrument. The comparison showed that the production-related components mostly reached Level 2 (Formal), with practices such as process mapping, bottleneck identification, and improvements to transport routes to reduce downtime. Furthermore, the sectorized placement of material was optimized, aligning unloading and compaction capacities.

These results validate the effectiveness of the method proposed by Ronceros et al. (2025) in mining environments. In addition, key lessons were identified, such as the consolidation of collaborative planning, the systematic use of process mapping, and a greater understanding of work levels (TP, TC, and TNC), fostering the internalization of Lean principles.

RESULTS

Table 1 and Table 2 show the maturity development of the MMDPLC components in six of the eight target conditions achieved during the application of Kaizen events. In the planning component, progress was made from level 1 to level 2 through the use of performance indicators and the application of Operations Science principles, such as batch theory, promoting the division of labor into smaller units and the sectorization of the material placement platform.

In the standardization component, progress was made from level 0 to level 2, establishing a common language for measuring cycle times in production, transport, and material placement. Compaction ratios were also standardized, aligned with concepts such as work in progress, throughput, lead time, and capacity.

Table 1: MMDPLC component maturity levels defined for each condition

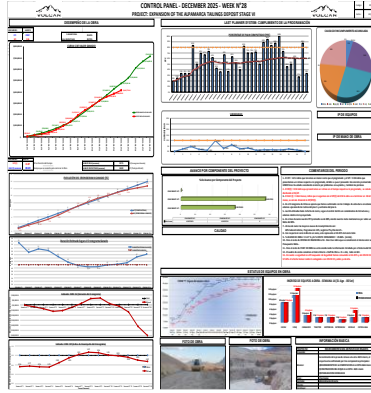
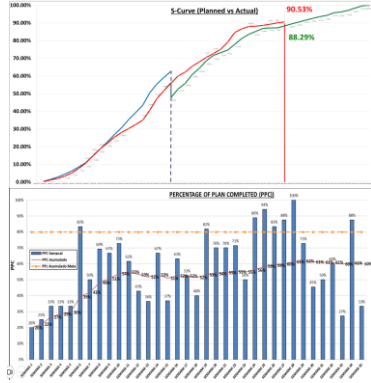
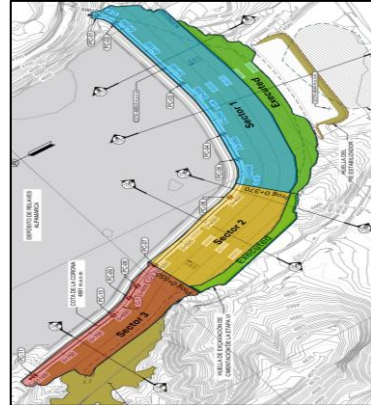
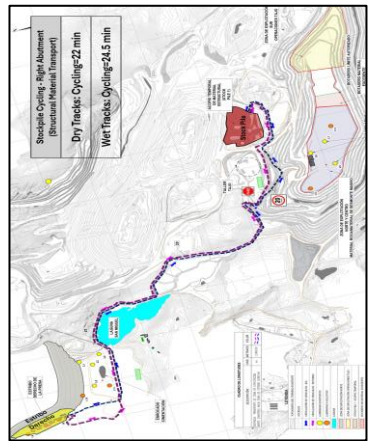
Component/Condition	Initial Condition	Achieved Condition	Illustration of the Achieved Condition
Management Practices	Level 1: Non-existent No rigorous project monitoring initiatives are documented.	Level 3: Established The adoption of good project management practices is encouraged, such as monitoring through Earned Value Management (EVM)	
Planning	Level 1: Initial Compliance with scheduled activities is not monitored on a week-by-week basis, and no performance metrics are in place.	Level 2: Formal Week-by-week feedback is implemented through tracking Percent Plan Complete (PPC).	
Planning	Level 1: Initial Execution is guided solely by instructions provided by the earthworks field technician.	Level 2: Formal The execution strategy is formalized through a work package breakdown, implemented via workface/area segmentation (sectorization).	
Standardization	Level 0: Non-existent No target ratios are defined for execution or for hauling material to the work fronts.	Level 2: Formal Target ratios for all project process flows are communicated to the technical management team through drawings and site walkthroughs.	

Table 1: MMDPLC component maturity levels defined for each condition (continued)

Component/ Condition	Initial Condition	Achieved Condition	Illustration of the Achieved Condition
Value	Level 0: Non-existent No attempts are documented to reduce cycling time or improve process flow within the production system.	Level 3: Established Standardized templates for process flow mapping were adopted, and cycle times were defined for each work front.	
	Level 1: Initial No strategies are used to manage production flow efficiently at the work fronts.	Level 3: Established Improvements to the production system at the work fronts are encouraged, supported by diagnostic tools such as the Balance Chart.	
	Level 1: Initial The company requires weekly constraint analysis to be included in the reports.	Level 2: Formal The work team is encouraged to identify and remove constraints to mitigate variability.	

In the value component, level 3 was reached through value stream mapping (VSM), identifying value-adding activities and reducing waste. This allowed the team to better understand and manage the production flow.

In terms of culture, progress was made from level 1 to level 2 by consolidating routines focused on flow and process, encouraging the identification of value in the production chain,

generating improvements and recognizing team initiatives, rewarding all those who generate an improvement proposal.

Overall, the maturity assessment facilitated the identification of opportunities for improvement and the implementation of concrete actions to strengthen the management of the production system.

DISCUSSION AND CONCLUSIONS

This study was conducted at a mining unit in the Peruvian Andes, located two hours from the nearest town and in an environment with extreme climatic conditions, common characteristics of mining in Peru. Unlike other experiences documented in the literature, such as those by Ronceros et al. (2025) and Perez et al. (2021), where MM are used to implement LC through structured methods, these studies are primarily developed in urban environments, such as building construction, and tend to focus on models based on the Last Planner System (LPS), which is widely studied in the literature.

This article documents the application of a generic five-stage implementation method, in combination with the MMDPLC, in a mining earthmoving project with high variability. The results show that the logic for adopting LC is consistent with that observed in building construction; however, it requires adapting the concepts to the earthmoving context and orienting production control toward the use of machinery, rather than manual labor. This constitutes a contribution by demonstrating the application of a maturity model that is rarely used in a type of project that is scarcely documented in the literature.

A key finding of this article is that the Maturity Model (MM) not only serves a diagnostic function but also acts as a structuring mechanism that translates Lean principles into concrete operational objectives. Furthermore, it allowed for the operationalization of concepts such as cycle times, bottlenecks, value identification, and work in progress, facilitating decision-making based on the actual behavior of the system. However, the results must be interpreted considering certain limitations. First, the study is based on a single case study, which restricts the generalizability of the findings. Second, the research was conducted using an action-research approach with high levels of researcher participation, which could introduce biases in the implementation and evaluation.

Despite these limitations, the study provides empirical evidence on the applicability of maturity models in relatively unexplored mining contexts. Future work should expand validation across multiple mining projects, given that almost all mines in Peru are located in similar geographical areas. It should also incorporate metrics and delve deeper into the adoption of Lean Construction to improve reliability and performance in highly variable production systems.

From a practical perspective, the results suggest that Lean implementation in mining projects should not be approached as the isolated adoption of tools, but rather as a redesign of the production system focused on flow management. In this context, controlling operational variables such as cycle times, work in progress, and capacity is fundamental to reducing variability and improving system reliability. The case study evidence shows that practices such as face sectorization, defining production rates, and systematically identifying bottlenecks generate more sustainable improvements than the fragmented application of Lean tools.

This study contributes to bridging the gap between Lean theory and practice in mining and demonstrates that maturity models allow for the translation of principles into operational practices, improving reliability and performance in highly complex projects. Future research should focus on developing higher levels of maturity and evaluating the long-term sustainability of clean energy practices. It should also document applications with different mining management systems (MMs) that have not yet been used in the literature. This will help

determine the suitability and appropriateness of some of these systems for this type of project and under the specific conditions of mining projects.

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