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LEAN PRACTICES AND THE GOVERNANCE OF MODERN METHODS OF CONSTRUCTION: ARTICULATION OF PLANNING HORIZONS IN MMC-BASED PRODUCTION SYSTEMS

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ABSTRACT

The construction industry is increasingly adopting Modern Methods of Construction (MMC) to improve productivity, predictability, and integration across project stages. While Lean Construction is widely recognized as a key enabler of MMC, existing research has primarily examined Lean practices in isolation or emphasized short-term planning routines, offering limited insight into how these practices are articulated across planning horizons and governed in practice. This study investigates how Lean practices are distributed and articulated across planning horizons in MMC-based production systems, and how digital support shapes the governance of planning and control across off-site and on-site operations.

The study integrates empirical evidence from multiple Brazilian construction projects to identify cross-cutting patterns. It finds Lean practices are more mature at the operational level but remain weak at strategic and tactical layers—especially in medium-term planning and off-site logistics. Digital tools improve transparency and coordination, yet they alone do not ensure effective articulation across planning horizons.

The paper contributes to Lean Construction theory by showing that, in MMC-based production systems, the Last Planner System (LPS) can be interpreted not only as a planning and control system, but also as a governance-oriented mechanism for aligning decisions, commitments, and information across planning horizons.

KEYWORDS

Lean Construction, modern methods of construction, planning horizons, governance.

INTRODUCTION

Construction faces persistent productivity and planning-reliability challenges, particularly in Brazil, where fragmentation and low industrialization increase non-value-adding work. Modern Methods of Construction (MMC) has been adopted as a pathway to improve predictability and system performance (Formoso et al., 2002; Koskela, 2000; Santos et al., 2020). In response, both globally and in Brazil, the industry has increasingly turned to MMC as a pathway to improve productivity, predictability, and overall system performance (Pan et al., 2018).

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In this study, MMC are understood as a broad set of industrialized approaches that redistribute production activities across factories, logistics networks, and construction sites. These include off-site manufacturing, prefabrication, modular and hybrid systems, standardized components, and digitally supported planning and production processes (Gibb, 1999; Lessing et al., 2015; Pan et al., 2018). Despite their technical diversity, MMC-based production systems share the common objective of reducing on-site variability and improving the coordination and integration of production flows across project stages (Blismas et al., 2006).

Lean Construction provides a well-established conceptual foundation for understanding and improving such systems, particularly through the design and governance of production systems capable of reliably transforming plans into coordinated action. Within this context, the Last Planner System (LPS) is widely recognized as a multi-layered planning and control system integrating long-term, medium-term, and short-term decision-making (Ballard, 2000; Ballard and Tommelein, 2016). However, empirical studies consistently report uneven LPS implementation, with a predominant focus on short-term control and persistent challenges in articulating planning horizons (Hamzeh et al., 2012). In this study, planning horizons refer to the long-, medium-, and short-term layers through which strategic intent is translated into executable work and operational commitments

In parallel, research on MMC-based production systems has reported productivity and flow improvements associated with Lean practices, yet these studies tend to focus on localized applications rather than system-wide coordination. Similarly, digital tools such as BIM and production monitoring systems are often examined in isolation, with limited empirical insight into their role in supporting the integration of planning horizons (Sacks et al., 2010; Dave et al., 2016). As a result, there remains limited understanding of how Lean practices are articulated across planning horizons in MMC-based production systems, particularly when supported by digital infrastructures. Accordingly, this paper examines how Lean practices are distributed and articulated across planning horizons in MMC-based production systems, and how digital support influences coordination between off-site and on-site operations

LITERATURE REVIEW

THE LPS AS A MULTI-LAYERED PLANNING AND CONTROL SYSTEM

Since its original formulation, LPA|S has been conceptualized as an integrated set of processes linking long-term planning, medium-term lookahead planning, and short-term commitment management, with the objective of improving workflow reliability by progressively transforming what should be done into what can, will, and did get done (Ballard, 2000). Subsequent empirical studies have reinforced this multi-layered conception, while also highlighting persistent challenges in aligning planning horizons in practice. Evidence from IGLC research shows that LPS implementation is often uneven, with stronger emphasis on short-term control practices and weaker articulation at medium- and long-term levels, limiting its effectiveness as a coherent planning system (Hamzeh et al., 2012; Ballard and Tommelein, 2016). For the purposes of this study, long-term planning is associated with strategic decisions related to overall production configuration, major sequencing logic, capacity, and key interfaces; medium-term planning is associated with lookahead, constraint removal, readiness, and coordination among design, supply, logistics, manufacturing, and site operations; short-term planning is associated with commitment planning, daily/weekly control, and learning from execution.

Importantly, much of the foundational and empirical research on LPS has been developed in the context of traditional, site-based construction, where assumptions regarding production flows, task interdependencies, and information availability primarily reflect on-site conditions. More recent IGLC studies have expanded the understanding of planning reliability,

coordination, and decision-making by examining maturity models, planning stability, and digital support for planning routines (Bellaver et al., 2022; Barth and Formoso, 2024; Etges and Caten, 2023; Conte et al., 2024). Despite these advances, empirical evidence remains limited on how Lean practices are articulated across planning horizons in MMC-based production systems, particularly in distributed environments involving off-site production and complex logistics interfaces.

DIGITAL TOOLS AND INFORMATION FLOW IN LEAN CONSTRUCTION

The increasing adoption of digital tools in construction has been widely discussed as a potential enabler of Lean principles. Research at the IGLC has explored the interaction between Lean Construction and Building Information Modeling (BIM), highlighting benefits related to visualization, coordination, and information transparency (Sacks et al., 2010). Other studies have proposed frameworks for improving information flow in Lean production systems, emphasizing the importance of timely and reliable data to support decision-making (Dave et al., 2016).

Despite these advances, digital technologies are often examined as isolated tools or applications, rather than as integral components of a broader planning and control system (Sacks et al., 2010; Dave et al., 2016; Barth and Formoso, 2024; Conte et al., 2022). The role of digital infrastructures in supporting coordination across planning horizons remains underexplored, particularly when considering the uneven articulation typically observed across LPS layers (Hamzeh et al., 2012).In many cases, digital tools are associated with specific planning levels—such as BIM for design coordination or digital visual management for short-term control—without explicit analysis of how information is shared, transformed, and governed across layers

Consequently, although the literature acknowledges the importance of information flow for Lean implementation, it still provides limited empirical insight into how digital tools contribute to the systemic integration of planning horizons, particularly in complex production environments (Dave et al., 2016; Barth and Formoso, 2024).

LEAN PRACTICES IN MMC-BASED PRODUCTION SYSTEM

A growing body of research has examined the application of Lean principles in modular and off-site construction contexts, reporting productivity improvements, waste reduction, and quality gains associated with Lean practices in prefabrication facilities and modular projects (Lu et al., 2020). However, these contributions tend to focus on localized efficiency gains, either within factories or at construction sites, offering limited insight into broader coordination challenges. Studies addressing off-site construction more broadly acknowledge the increased complexity arising from fragmented production locations and extended supply chains (Ogunbiyi et al., 2020; Pan and Sidwell, 2011), yet rarely examine how Lean planning systems are structured across multiple planning horizons to manage such complexity.

When the Last Planner System is discussed in modular and off-site construction contexts, its application is typically concentrated at the operational level, supporting short-term production control either in factories or on site, while the articulation of medium- and long-term planning across off-site and on-site operations remains largely implicit. Recent Brazilian IGLC studies have explored MMC adoption from perspectives such as logistics planning, standardization, production flow, and off-site integration (Cunha et al., 2025; Antonini et al., 2023; Hsu et al., 2018), but continue to emphasize localized applications or individual practices. Taken together, the literature indicates that although LPS is theoretically framed as a multi-layered planning and control system and coordination challenges across planning horizons are well recognized, there remains limited empirical understanding of how Lean practices are

distributed and articulated across planning horizons in MMC-based production systems, particularly when supported by digital infrastructures and complex logistics interfaces.

Taken together, the literature suggests three unresolved issues: the uneven implementation of LPS across planning horizons, the limited empirical understanding of cross-horizon coordination in MMC contexts, and the insufficient explanation of how digital support contributes to governance across distributed production systems

RESEARCH METHOD

This study adopts an integrative empirical research approach, combining evidence from multiple empirical studies conducted within Brazilian construction companies with a structured synthesis of relevant Lean Construction and MMC literature. The methodological design is aligned with the research objective of understanding how Lean practices are articulated across planning horizons and how such articulation supports the governance of planning and control in MMC-based production systems.

Rather than reporting a single intervention or case, the paper builds on a cumulative body of empirical investigations carried out by the authors over several years in diverse production contexts. Collectively, these studies provide a rich empirical basis for identifying recurring patterns of coordination, decision-making, and governance across off-site and on-site operations.

EMPIRICAL CONTEXT

The empirical material comprises studies conducted in Brazilian construction companies operating in contexts characterized by varying degrees of industrialization, production scale, and organizational complexity. The empirical corpus comprises 12 studies conducted in companies/projects between 3 years, covering four main context groups: (1) industrialized and modular construction companies delivering integrated solutions across design, manufacturing, logistics, and on-site assembly; (2) large residential developers implementing lookahead planning, Takt Planning, and digital tools to enable scalability across multiple sites; (3) major infrastructure projects, such as highways, airport runways, and renewable energy facilities, where Lean principles were adapted to manage large-scale, distributed production systems; and (4) productivity and waste analysis studies across multiple construction sectors using the Work Sampling Method to diagnose value-adding and non-value-adding activities.

Data collection across the empirical studies combined qualitative and quantitative methods, including semi-structured interviews with representatives from design, planning, production, logistics, and management; direct and participant observation of manufacturing and construction processes; participation in planning and control meetings and workshops; analysis of company documents, production plans, and digital databases; and surveys assessing perceptions of planning effectiveness. For this paper, the analysis focused on identifying cross-cutting patterns rather than comparing individual cases, synthesizing empirical evidence around three analytical dimensions: the distribution of Lean practices across planning horizons, the role of digital tools in supporting coordination and information flow, and the governance mechanisms through which planning and control decisions are aligned across off-site and on-site operations. Triangulation across data sources and contexts was used to enhance the robustness of the findings.

The integrative nature of the study entails certain limitations. Rather than comparing individual cases, projects were grouped by typology to capture recurring planning and governance challenges associated with distinct production configurations. Table 1 summarizes the main project types considered and their relevance to the research question.

This study does not aim at statistical generalization. Its contribution lies in analytical generalization across multiple empirical contexts. Because the synthesis is based on cases

previously investigated by the authors and grouped by typology rather than compared one by one, the findings should be interpreted as recurrent patterns observed in Brazilian MMC-related contexts rather than universal characteristics of all MMC production systems.

Table 1: Project type correlation with the research question

Project type	Typical production configuration	Main planning and governance challenges	Relevance to the research question
Industrialized building projects	Distributed production across factories, logistics networks, and on-site assembly	Alignment of strategic decisions with factory capacity, logistics constraints, and on-site sequencing	Reveals how Lean practices govern planning across spatially distributed production
Large-scale residential developments	Repetitive production across multiple sites with shared resources	Coordination of tactical and operational planning at scale; consistency of planning practices across sites	Enables analysis of governance mechanisms supporting scalability in MMC contexts
Infrastructure projects with MMC elements	Temporarily configured production systems with high uncertainty	Governance of planning under time pressure, changing interfaces, and long supply chains	Highlights how planning horizons are articulated in complex, non-repetitive MMC environments
Renewable energy projects (wind and solar)	Strong coupling between manufacturing, transport, and on-site installation	Synchronization of off-site production, logistics, and site readiness	Illustrates governance challenges where flow reliability is critical to system performance
Cross-sector productivity studies	Multiple project typologies analyzed comparatively	Identification of systemic inefficiencies affecting planning reliability	Provides system-level context for understanding governance gaps across MMC maturity levels

RESULTS

Results are presented in three parts: (1) the distribution of Lean practices across planning horizons, (2) governance-related mechanisms emerging from planning and control routines, and (3) the role of digital support in connecting off-site and on-site operations.

Strategic and medium-term practices—especially off-site logistics, capacity planning, and interface management—remain less mature and weakly articulated, with limited integration between long-term plans and upstream supply chains. Medium-term routines support feasibility and interface coordination but are often underused compared to short-term control, particularly in industrial and infrastructure projects. Digital coordination structures like the Control Tower help connect horizons by integrating performance and planning data, yet overall articulation remains unbalanced, leaving governance gaps that constrain full MMC integration (Table 2).

Table 2 synthesizes the recurring presence of Lean practices across the empirical corpus. A check mark indicates that a practice was identified in at least one empirical unit within that project category; it does not indicate implementation intensity or maturity by itself.

GOVERNANCE MECHANISMS EMERGING FROM LEAN PRACTICES IN MMC-BASED PRODUCTION SYSTEMS

The findings suggest that, in the analyzed MMC-related contexts, Lean practices perform a governance-supporting role by coordinating decisions, commitments, and information across organizational boundaries. A recurring mechanism is constraint-based coordination, via lookahead planning, constraint identification, and readiness criteria. These practices mediate negotiations on priorities, sequencing, and resource allocation across design, procurement, logistics, manufacturing, and site operations. However, constraint management remains mostly

tactical/operational, with limited linkage to strategic capacity and supply-chain configuration decisions.

A second governance mechanism emerges through commitment management and performance feedback. Indicators such as Percent Plan Complete (PPC), adherence to takt rhythms, and compliance with readiness criteria are widely used to monitor execution and support corrective action. These indicators function as coordination devices by making deviations visible and triggering collective responses during planning and control meetings. The empirical studies show that these mechanisms are most mature at the operational level, where short-term commitments are regularly reviewed and adjusted. In contrast, similar feedback loops are less developed at the strategic and tactical levels, limiting learning across planning horizons.

Table 2: Application of lean tools in different projects types

Lean Practice	Solar	Wind power	Railways	Sanitation	Mining	Industry	Highways
LPS (LPS)	✓	✓	✓	✓	✓	✓	✓
Control tower	✓	✓	✓	✓	✓	✓	✓
Line of Balance Sheet / Takt	✓	✓	✓	—	—	✓	✓
Kaizen / A3	✓	✓	✓	✓	✓	✓	✓
Lookahead Planning	✓	✓	✓	✓	✓	✓	✓
Lean Ramp-Up	✓	✓	✓	✓	✓	✓	✓
Demobilization Planning	✓	✓	✓	✓	✓	—	✓
Team Training	✓	✓	✓	✓	✓	✓	✓

The empirical evidence also highlights the role of standardization combined with local adaptation as a governance mechanism. Standardized work packages, predefined logistics kits, takt structures, and visual planning templates are used to stabilize production and reduce variability, particularly in repetitive residential and industrialized contexts. At the same time, flexibility is maintained through localized adjustments during weekly and daily planning cycles. This balance between standardization and adaptability enables coordination across multiple sites and production stages, but the findings indicate that such mechanisms rely heavily on human mediation and are only partially supported by integrated digital systems.

Across all project types, the Control Tower emerges as a transversal governance mechanism that connects planning horizons by consolidating production performance, constraints, logistics status, and planning reliability to enable cross-level visibility and coordination. Beyond monitoring, it supports decision-making through early deviation detection, alignment between off-site production and on-site needs, and shared situational awareness among stakeholders, operating across strategic, tactical, and operational levels. However, persistent governance gaps remain: strategic decisions on off-site capacity, logistics configuration, and long-term sequencing are often weakly linked to tactical and operational controls, keeping governance reactive rather than anticipatory and limiting the role of medium-term planning in translating strategic intent into executable work—suggesting that Lean's cross-horizon governance potential in MMC systems is still not fully realized. These gaps were particularly visible where medium-term planning was weakly connected to procurement and supply decisions, reducing

the ability of project teams to translate strategic intent into material readiness, logistics synchronization, and executable work

THE ROLE OF DIGITAL SUPPORT IN ARTICULATING PLANNING HORIZONS IN MMC-BASED PRODUCTION SYSTEMS

The empirical evidence indicates that digital tools play a supporting but non-deterministic role in articulating planning horizons in MMC-based production systems. Across the analyzed contexts, digital solutions are consistently used to enhance visibility, information flow, and monitoring of production performance; however, their contribution to governance depends on how they are embedded within Lean planning routines rather than on technological sophistication alone.

At the operational level, digital support is most mature and consistently applied. Visual management boards, digital dashboards, and real-time progress monitoring systems are widely used to track daily production, manage commitments, and support short-term decision-making. These tools increase transparency, facilitate rapid feedback, and reinforce execution discipline, particularly when integrated with daily and weekly planning routines. In several empirical contexts, digital visual management complements physical boards, extending visibility beyond the site and enabling remote coordination among stakeholders.

At the tactical level, digital tools support medium-term planning by consolidating constraints, readiness, and interface information across design, procurement, manufacturing, logistics, and site operations. However, integration remains fragmented across multiple systems, limiting links between tactical decisions, strategic intent, and operational execution—especially in infrastructure and remote projects where connectivity constraints exacerbate the issue.

At the strategic level, the use of digital tools is more selective and less standardized. Long-term planning, capacity definition, and logistics configuration are sometimes supported by digital planning models and BIM-based simulations. Nevertheless, the empirical evidence suggests that these tools are not consistently connected to tactical and operational data streams. As a result, strategic decisions related to off-site production capacity, logistics sequencing, and supply chain configuration are only partially informed by feedback from execution, reducing the potential for anticipatory governance across planning horizons.

A prominent finding across all project types is the emergence of the Control Tower as a digital-enabled coordination structure operating transversally across planning levels. Rather than functioning as a standalone software solution, the Control Tower integrates performance indicators, constraint information, logistics status, and planning data from multiple sources. This integration enables cross-level visibility and supports coordination between off-site and on-site operations. The empirical evidence shows that the Control Tower's effectiveness is strongly dependent on its alignment with Lean planning routines, particularly LPS meetings and coordination forums, reinforcing its role as a governance mechanism rather than merely a monitoring tool.

Despite these advances, the findings indicate that digital support alone does not resolve articulation gaps between planning horizons. Where Lean routines are weak or inconsistently applied—especially at the medium-term level—digital tools tend to reinforce existing silos rather than integrate them. Conversely, in contexts where planning routines are well established, digital tools enhance governance by supporting transparency, feedback, and alignment across strategic, tactical, and operational decision-making.

Overall, the empirical evidence suggests that digital tools in MMC-based production systems function primarily as enablers of governance, amplifying the effects of Lean planning practices. Their contribution to articulating planning horizons depends less on technological capabilities and more on how they are embedded within the planning and control system.

The synthesis presented in Table 3 and Figure 1 highlights how Modern Methods of Construction are operationalized through Lean practices across different planning horizons. Rather than acting as isolated techniques, these practices collectively shape governance mechanisms that coordinate decisions, commitments, and information flows in MMC-based production systems. The findings indicate that while operational control practices are relatively mature, persistent gaps remain in articulating strategic and tactical planning, particularly in relation to off-site logistics and digital integration. These patterns provide the empirical basis for the discussion that follows, which examines the implications of these governance dynamics for Lean theory and the design of MMC-based production systems. Figure 1 illustrates the practical alignment between the hierarchical layers of the LPS (LPS) and the Lean–MMC practices observed in Brazilian construction projects. This mapping reinforces how Lean Construction mechanisms serve as the operational foundation for implementing MMC strategies across all planning levels and time horizons.

DISCUSSION

Empirical evidence shows that Lean practices are concentrated at the operational level of the LPS, while strategic and tactical layers remain less integrated. Digital tools improve visibility and monitoring, but governance depends mainly on the articulation between Lean routines, planning forums, and information flows. When this connection is weak, especially between long-term planning and medium-term feasibility, governance becomes reactive and limits MMC systems' ability to manage complexity remains reactive, limiting the ability of MMC systems to anticipate and manage complexity.

Table 3: MMC and lean practices used

MMC category	Lean practices observed	Planning horizons	Governance contribution
Modular construction and off-site manufacturing	Lean Ramp-Up, Demobilization Planning, Kaizen / A3	Strategic, Tactical, Operational	Coordination of production start-up, sequencing, and learning across off-site and on-site operations
Digital planning tools and BIM integration	Control Tower, Constraint Management, Team Integration	Tactical, Operational	Integration of information flows, visibility of constraints, and cross-level decision support
Production flow systems	Line of Balance, Takt Planning, Lean Ramp-Up	Strategic, Tactical	Structuring and stabilization of production flow across repetitive and non-repetitive contexts
Standardized work packages and prefabricated components	Kaizen / A3, Demobilization Planning, Balance Sheet	Tactical, Operational	Reduction of variability and alignment between standardization and execution flexibility
Collaborative planning systems	LPS (LPS), Control Tower, Constraint Management	Strategic, Tactical, Operational	Governance of commitments, coordination of interfaces, and alignment of planning horizons

THEORETICAL IMPLICATIONS FOR THE LPS

The findings contribute to Lean Construction theory by extending the understanding of the LPS beyond its traditional interpretation as a set of planning routines. While the LPS is frequently described in the literature as a multi-layered system integrating long-term, medium-term, and short-term planning, empirical studies have often focused disproportionately on short-term

control. This study provides empirical evidence that reinforces this imbalance and highlights its governance implications in MMC-based production systems.

Rather than functioning as a fully articulated system, the LPS is frequently implemented as a collection of partially connected layers. The operational layers (WILL and DID) are comparatively robust, whereas the tactical (CAN) layer remains underdeveloped in its role of translating strategic decisions into executable work. This limited articulation constrains the ability of the LPS to govern complex production systems characterized by distributed manufacturing, logistics interdependencies, and off-site/on-site integration

By analyzing Lean practices through the lens of planning horizons, this study reframes the LPS as a governance structure, where effectiveness depends on the alignment of decision-making authority, information flow, and commitment negotiation across layers. The findings suggest that strengthening the medium-term planning layer is critical for enabling the LPS to function as an integrative governance mechanism in MMC contexts, rather than primarily as a short-term control system.

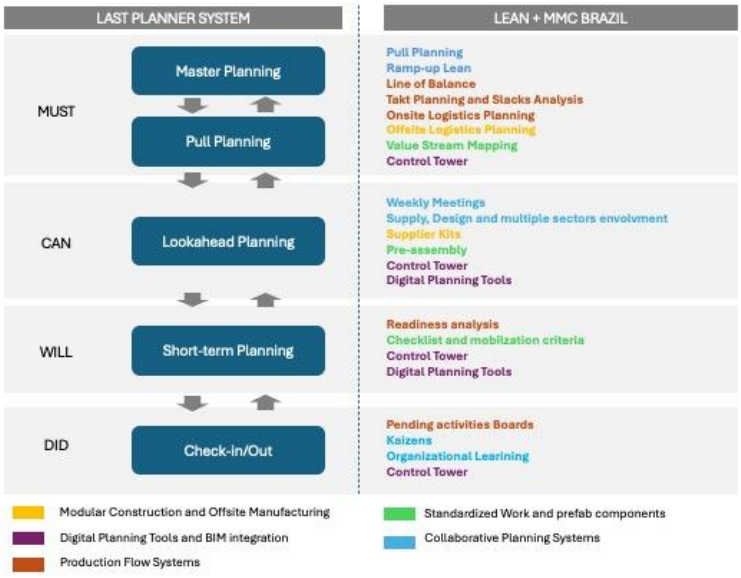

Figure 1: MMC and lean practices used

GOVERNANCE AND THE ROLE OF DIGITAL SUPPORT IN MMC-BASED PRODUCTION SYSTEMS

The study also advances the understanding of governance in MMC-based production systems by clarifying the role of digital support. While digital tools are often presented in the literature as enablers of Lean implementation, the findings indicate that their contribution to governance is contingent upon their integration with planning routines and decision-making processes. Digital dashboards, BIM-based planning tools, and monitoring systems enhance transparency and facilitate coordination, particularly at the operational level. However, when planning routines are weak or fragmented—especially at the tactical level—digital tools tend to reinforce existing silos rather than integrate planning horizons. This challenges technology-centric narratives and underscores the importance of organizational routines and governance structures in realizing the potential of digitalization.

Rather than acting merely as a monitoring tool, the Control Tower functions as a transversal governance mechanism that integrates performance data, constraints, and planning information across strategic, tactical, and operational levels. This finding suggests that digital support contributes most effectively to governance when it enables cross-level visibility and supports collective decision-making, rather than when it is deployed as an isolated technological solution.

While prior research has acknowledged the layered nature of the LPS and the potential synergies between Lean and MMC, few studies have investigated how these layers are governed in practice, particularly in relation to off-site production and digital integration. By synthesizing empirical evidence across multiple project types and MMC contexts, this paper demonstrates that the key challenge lies not in the absence of Lean practices, but in their uneven articulation across planning horizons.

In doing so, the paper offers a theoretically grounded and empirically supported perspective on Lean Construction as a governance framework for industrialized construction, providing a foundation for future research on the design and governance of MMC-based production systems.

IMPLICATIONS FOR PRACTICE AND FUTURE RESEARCH

The findings of this study indicate that the potential of MMC is realized through the systematic articulation of Lean practices across planning horizons. Performance improvements were associated with the implementation of Lean as an integrated planning and governance system. In this context, treating the LPS as a multi-layered governance structure proved particularly relevant, as operational-level practices tend to be more mature than strategic and tactical planning layers. Collaboration emerged as a critical enabling condition, with multidisciplinary participation in planning routines supporting coordination across design, manufacturing, logistics, and on-site operations. Digital visual management and performance dashboards contribute most effectively when embedded in Lean routines, with structures such as the Control Tower functioning as integrative coordination mechanisms across planning horizons rather than standalone monitoring solutions.

The findings also open field for future research in Lean Construction and MMC. While recurring governance patterns were identified, further quantitative studies are needed to assess how different configurations of Lean practices and planning articulation affect key performance indicators across MMC contexts. In addition, deeper investigation is required into how specific digital configurations—such as BIM–LPS integration, automated constraint management, and advanced planning analytics—support governance in practice, as well as how slack, resilience, and knowledge creation through Lean planning routines contribute to sustained performance improvement in MMC-based production systems.

CONCLUSIONS

This study examined how MMC are articulated with Lean Construction practices, with a particular focus on planning horizons, governance, and digital support. The findings indicate that the benefits of MMC are closely linked to the systematic application of Lean principles, especially through the LPS, which supports planning reliability, workflow stability, and learning across production stages. The study also contributes to Lean Construction theory by conceptualizing the LPS as a governance mechanism that articulates planning horizons in MMC-based production systems. It further shows that the effectiveness of MMC depends on the coordination of Lean practices across organizational and temporal boundaries, and that digital tools primarily support governance when embedded in established planning routines.

Empirical evidence shows that practices such as Takt Planning, Visual Management, performance dashboards, and logistics planning contribute to reducing waste, improving coordination, and enhancing transparency when they are coherently integrated across strategic, tactical, and operational levels. The study also highlights the growing role of digital-enabled structures, such as the Control Tower, in supporting cross-level visibility and data-informed decision-making.

Overall, the results suggest that the transformation towards Lean-based MMC is a gradual and multifaceted process. While significant progress has been achieved in improving planning and production control, persistent challenges remain in articulating planning horizons,

integrating off-site logistics, and strengthening organizational learning and collaboration. Addressing these challenges is essential for advancing the governance of MMC-based production systems and for achieving sustained performance improvement in the construction sector. Rather than offering statistical generalization, the paper identifies recurring patterns across Brazilian MMC-related contexts. Within these limits, the study suggests that the benefits of MMC depend not only on the adoption of isolated Lean practices, but on the degree to which such practices are articulated across planning horizons and embedded in routines that connect strategy, logistics, manufacturing, and site execution.

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