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UNDERSTANDING THE DESIGN PROCESS IN MODULAR CONSTRUCTION PROJECTS BASED ON VALUE STREAM MAPPING

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ABSTRACT

Design management in modular construction (MC) faces additional challenges in relation to traditional projects due to compressed lead times, increased customization demands, and interdependency between production units. These factors amplify uncertainty and require continuous decision-making under evolving conditions. Value Stream Mapping (VSM) is a powerful approach for reducing the share of non-value-adding activities of design flows and enhancing cross-sector integration. The main goal of this investigation is a set of guidelines for improving the MC design process, especially regarding planning and control. VSM was used as a diagnostic tool in the design process of a MC company from Brazil, allowing the identification of improvement opportunities in design flow. Design Science Research (DSR) was the methodological approach adopted in this investigation, being structured in iterative cycles of diagnosis, development, and evaluation. Data collection involved semi-structured interviews, direct observations, and interdisciplinary seminars. The proposed future-state VSM highlights opportunities to reduce project lead times by up to 75%, emphasizing collaborative design reviews, set-based design principles, and formal collection of client requirements. Findings suggest that VSM is an effective tool for streamlining workflows, reducing rework, and improving stakeholder coordination. This research contributes both theoretically and practically by advancing knowledge on how to deal with the type of complexity that exists in MC, providing actionable strategies for enhancing design efficiency and predictability.

KEYWORDS

Value Stream Mapping; Design Management; Modular Construction; Process Optimization; Complexity.

INTRODUCTION

Design management in Modular construction (MC) faces additional challenges compared to conventional design, due to very short project lead times, a wide range of material suppliers, and the demand for customization, which increases uncertainty and requires decisions based on frequently changing requirements. These factors require some mechanisms for coping with complexity and the need for resilience (Saurin et al., 2013). The complexity of the design

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process in this context is often underestimated, and as this is the first stage of construction projects, it may significantly impact manufacturing and assembly (Bulhões and Picchi, 2011).

One of the major challenges in design management is that several organizations are involved and come together temporarily to deliver construction projects (Wesz et al., 2018; CIH, 2023). This fragmentation hinders integration and negatively affects efficiency (Shuker and Tapping, 2010). In this context, the Lean Production philosophy can contribute to the management of complex projects by providing concepts and methods to understand dynamic interactions and reduce variability (Saurin et al., 2013). Integrating several components and materials demands a high degree of coordination among multiple disciplines (architecture, structural design, etc.). Furthermore, the decentralization of production and design activities in some industrialized construction projects demands the capacity of the design teams to handle the increased interactions resulting from this fragmentation (Amaro et al., 2024).

Value Stream Mapping (VSM) has been previously used to analyse processes in engineering-to-order (ETO) production systems (Bulhões and Picchi, 2011). ETO production systems can be defined as the ones in which the customer order decoupling point is located at the design stage, i.e., the customer order is delivered at the beginning of the design phase of a product (Gosling and Naim, 2009). However, MC companies must also manage the complexity of numerous components, some of which are repetitive. By contrast, others are custom-made for the client (CIH, 2023), which demand flexibility from the supply chain in terms of product mix and deadlines (Voordijk, 2006). VSM has also been applied in the design processes of prefabricated product manufacturers (Bulhões and Picchi, 2011), providing evidence that this tool is effective for mapping and improving design flow and enhancing integration among design teams. However, none of the previous studies have explored the use of VSM for MC design, a context that presents unique challenges, distinguishing it from traditional projects or other types of industrialized construction. The MC design process must consider a wide range of requirements, including the ones demanded by end-users, constraints from the manufacturing plant, and site installation constraints. There are also interdependencies among different design disciplines, some internal to the company and others externally contracted. These factors create a complex chain of interactions and introduce significant uncertainties into the system, as most of the complexity of product development and design is integrated into a single, highly interdependent system (CIH, 2023).

Moreover, MC differs from other industrial contexts in two fundamental aspects. First, there is a strong interdependence between sectors, requiring integrated planning and control that involves design, manufacturing, logistics, and assembly (Wesz et al., 2018). Second, the supply chain in MC is significantly more complex than in other industrialized systems due to the diversity of components and the need for agile decision-making in the design phase to enable procurement and assembly (Voordijk, 2006). Therefore, the knowledge gap addressed in this investigation is the need to devise new approaches for design planning and control that are suitable to the context of MC. This study aims to understand the challenges and opportunities to improve the design process in MC by analyzing interdependencies among the main stakeholders and other supply chain members. For this purpose, VSM has been used as a diagnostic tool, allowing the identification of improvement opportunities in the design flow. Accordingly, the research is guided by the following question: How to deal with complexity attributes in the design process of MC? The main outcome of this investigation is a set of guidelines for improving the MC design process, especially regarding planning and control.

DESIGN PROCESSES IN MODULAR CONSTRUCTION

William (1999) defines complexity in projects as the result of many dynamically interacting elements. The interdependence between different sectors and disciplines results in nonlinear flows and iterative processes. In industrialized construction, complexity tends to increase due to very short lead times (Wesz et al., 2018), which increases simultaneity and the need for collaboration (Amaro et al., 2024). This contributes to raising variability (Saurin et al., 2013), an undesirable and difficult-to-predict characteristic that can negatively impact operations. Moreover, the design process in MC companies has a distinct characteristic: every project necessitates a design for manufacturing and another one for site installation, requiring tight integration of logistics, production, and assembly, as design decisions have a direct impact on the subsequent stages (Wesz et al., 2018). In this context, production systems need to be resilient to absorb the impacts of variability, maintaining functionality even amid emerging events (Saurin et al., 2013).

VALUE STREAM MAPPING (VSM)

The design process is one component of the value flow—from production to client delivery (Rother and Shook, 2003). Building design contains transformation activities, which convert customer needs and expectations into products and process new information, and also non-value-adding activities, such as transferring, inspecting, waiting, and rework, among others (Koskela, 2000). Erikshammar et al. (2013) argue that VSM does not provide concrete facts for managerial decisions, only indicating directions and gaps, usually resulting in an action plan. It has been criticized for being static, describing only a specific moment in production (Sreram and Thomas, 2023). VSM does not analytically predict future impacts, functioning more as a discussion tool than as an analysis outcome (Rother and Shook, 2003). Due to these limitations, this study employed VSM in conjunction with other tools, which are explained in the research method section.

HIERARCHICAL MODULARITY

Unlike other industries in which it is more straightforward to define a product, construction products involve a combination of core repeatable components and customizations that are tailored to specific project needs (Rocha, 2011). Hierarchical modularity has emerged as a structured approach to product design that organizes construction elements into interdependent levels, balancing standardization and customization (Utzig et al., 2024). The development of a modular product platform requires meticulous planning to balance standardization with adaptability over time (Zieth and Rocha, 2024). Standardized interfaces (e.g., slot, bus, sectional; Ulrich, 1995) ensure interoperability between modules from diverse suppliers, enabling incremental evolution of platforms (Zieth and Rocha, 2024). Key to this process is aligning design with a sales approach in which requires client requirements are clearly identified (Rocha, 2011) so that the developed solutions meet a finite space of solutions and address market demands (CIH, 2023; Conte, 2024).

RESEARCH METHOD

The Design Science Research (DSR) methodological approach was adopted, which consists of devising a solution concept, named artifact, to solve classes of problems (Peffers et al., 2007). The whole research process was structured according to the DSR phases suggested by Vaishnavi and Kuechler (2007): understanding the problem, devising and implementing the artefact, and assessing the utility and applicability of the artefact. However, as this is an ongoing study, the results presented in this paper refer to the first phase, focused on problem analysis and formulation (Understanding). In this phase, the aim is to get a deep understanding of the problem so that it is framed, i.e. the problem is understood from a specific perspective, providing ideas for devising an innovative artefact. Within this phase, the research was divided into three main steps: (1) Interviews and document analysis for understanding the context of the company; (2) Mapping the design flow and proposing improvements; and (3) Validating data and establishing a set of guidelines.

In the first step, the goal was to analyse the entire product development process, from the commercial stage to the delivery of design information to the manufacturing plant and construction site. The interviews were conducted with a total of 5 participants, as shown in Table 1. The selection criteria included industry experience and direct involvement in decision-making. For instance, the project manager and engineering coordinator provided insights into the overall workflow, while the commercial and cost estimator identified economic constraints, and the designer highlighted operational challenges. This diversity enabled a comprehensive understanding of the process, allowing for the mapping of project stages, and the identification of existing waste and existing constraints. At the end of this step, a VSM of the existing design flow was produced. Thematic analysis was carried out by the authors, coding the transcripts to identify patterns and interdependencies within the processes.

In step 2, the future state VSM was devised. Based on the data collected in Step 1, it was possible to identify opportunities for improvement, especially in terms of eliminating non-value-adding activities. An iterative cycle (proposal, evaluation, and refinement) was undertaken until the final version of the future state map was produced.

The future-state VSM was assessed in the third step. A seminar involving several stakeholders was held to consolidate the findings and validate the proposals. Twelve company professionals participated in this seminar, including 5 engineers, 4 designers, 2 managers, and the company's CEO. Representatives of the research team also took part in the discussions, including 2 master's students, one PhD student, and 3 professors. One of the main topics discussed in the seminar was the interactions between commercial and detail design processes, which resulted in proposals for improving the design flow.

The final set of guidelines emphasized mechanisms to deal with complexity and the alignment of client demands with operational decisions, prioritizing integration between disciplines and the reduction of variability. These guidelines not only provide actionable strategies for streamlining design flows but also advance theoretical understanding of resilience in product development systems. While practical implementation remains the company's responsibility, this study makes a contribution towards a prescriptive framework for balancing efficiency and flexibility in design, offering insights into the role of VSM as a diagnostic and design tool in modular construction contexts. Potential biases in this approach include the subjectivity in the thematic analysis of interviews and the influence of participants' experiences on the formulation of guidelines. Additionally, the involvement of a limited number of stakeholders may restrict the generalization of the findings. To mitigate these risks, data triangulation was applied, incorporating multiple sources of evidence and validation by different professionals throughout the study, as shown in Table 1.

Table 1: Sources of evidence.

Source	Description	Involved	Aim
Semi-structured interviews	1 hour for each interview (5 hours)	Project manager, commercial project manager, cost estimator, product engineering coordinator and designer	Understand the commercial and detail design, main features, and challenges
Document analysis	Long-, Medium-, and Short-term plans, design documents	Company documents	Triangulation of VSM results wi the company's short-, medium and long-term planning.
Semi-structured interviews	3 meetings to identify design constraints (4 hours)	Project manager, cost estimator, product engineering coordinator	Identify design constraints and propose improvements for the future state VSM
MFV Seminar	2 hours	Managers and designers	Assess future VSM, present improvement suggestions

COMPANY DESCRIPTION

Company X operates in the delivery of complete projects involving prefabricated volumetric modules, manufacturing, logistics, and site assembly. Its main competitive advantage is delivering projects faster than traditional buildings, while ensuring quality and safety. For approximately 2.5 years, the company has implemented Lean Production concepts and methods in their processes. The company divides its operations into three main sectors: (I) Product Design and Engineering: the commercial design team interacts with client representatives in order to define initial project requirements and produce a conceptual design. The detail design team receives the basic design and develops manufacturing and assembly specifications from client inputs. The product engineering team is responsible for the analysis, development and prototyping of new product solutions; (II) Manufacturing: the modules are produced at the manufacturing plant, using standardized processes and quality control. (III) Logistics and Site Installation: after production, the modules are transported to the construction site, where they are assembled and integrated into the final project.

The products vary in typology and degree of customization. The company operates two main product lines: reinforced concrete heavy modules with a high degree of repetition, designed for prisons; and lightweight modules, designed for hospital, residential, and school segments. In this study, the focus was on lightweight modules, specifically those intended for the school segment, due to the high degree of variation among products and the high demand observed in this market. This selection enables exploration of modularity and customization, which are key to improving efficiency and meeting specific client needs.

DESIGN PLANNING AND CONTROL

The existing design planning and control system has been implemented in a previous study (Amaro et al., 2024), and it is strongly based on the Last Planner System© and on other Lean Construction methods. This system was divided into different planning levels (long, medium, and short term), consisting of five stages, organized into two interconnected phases, being connected to both planning and control systems from the manufacturing plant and site installation. A distinguishing feature of this system is its ability to address both single and multiple projects, which is necessary in MC, as the design team need to be involved simultaneously in different projects. The company adopted the policy that the planning process should be driven by site assembly, which sets deadlines and triggers for design and manufacturing in order to integrate different production units. The use of visual tools, such as management boards, helps to track task progress and support more informed decision-making. These tools helped reduce waiting times, synchronize activities whenever possible, and remove constraints throughout the process.

DEVELOPMENT OF THE VALUE STREAM MAP (VSM)

The VSM produced represents schematically the design process from contract to final delivery. Figures 2, 3, and 4 present the current state of VSM. These maps represent the main activities, including indicators for the start and end of manufacturing and the start and completion of site assembly. Figure 2 provides an overview of the activities, while Figures 3 and 4 present detailed representations of the design process. Due to the occurrence of parallel activities, the calculation of the Lead Time considered the three activity bands separately, each with variable influences on the manufacturing process: the blue band (Figure 3) covers design activities that are essential for defining the pace of production; the gray band (Figure 4) represents activities related to site assembly which are directly connected to manufacturing; The yellow band includes activities related to site assembly that have a limited impact on the production activities at the manufacturing plant. This division was adopted to identify the interdependencies between different groups of activities.

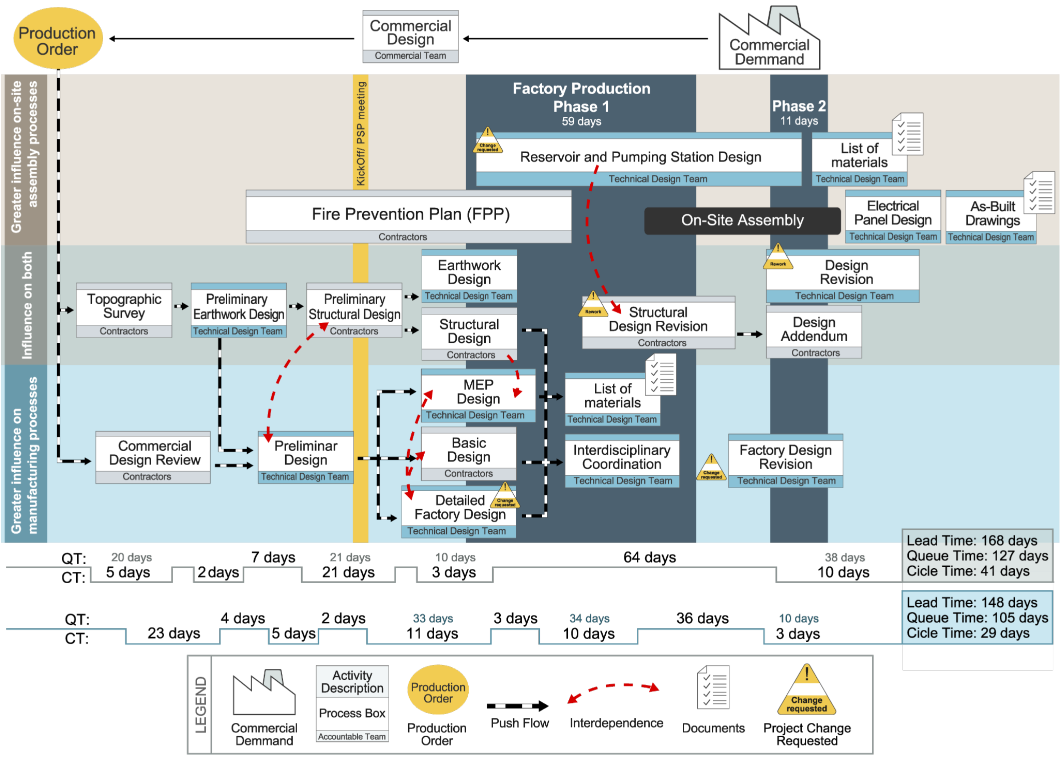

Figure 2: Current state VSM – General Visualization Scheme

Furthermore, the design flow is divided into multiple processes, some carried out internally (blue boxes) and others by outsourced teams (gray boxes). The duration of activities was calculated based on a five-day workweek. The process boxes in these maps are divided into five parts: process name; start date (SD) and end date of the processes (ED); cycle time (CT); queue time (QT); planned time (PT); team responsible for carrying out the process. Finally, the total CT of the selected processes was compared with the lead time (LT), taking into account all queue times and waiting periods throughout the flow. In the activity flow of Figure 3, the LT for the design activities was 148 days, while the CT was only 29 days. In addition to the waiting periods between one activity and another, a significantly long QT was observed compared to the CT, caused by internal revisions, unresolved design definitions, and rework from misalignment between the work teams.

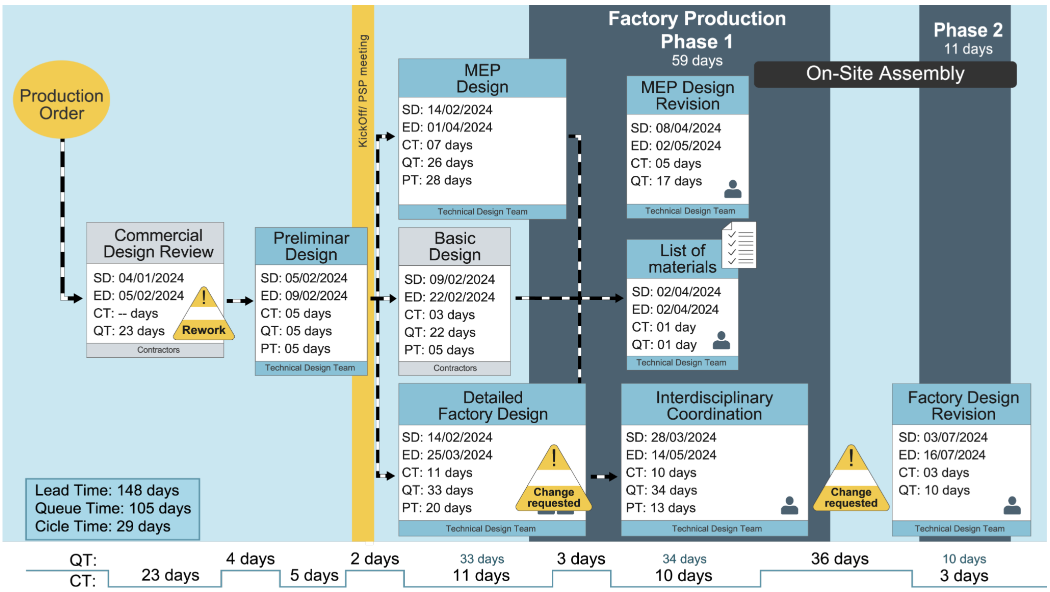

Figure 3: Current state VSM - factory design activities

The manufacturing design-related activities were analysed collectively and distributed according to the number of employees involved, considering the time spent by each collaborator. The same criterion was applied to the MEP activities. For parallel activities, those with the highest CT and QT were selected to calculate the LT line. In the activity flow presented in Figure 4, the criterion for choosing between parallel activities of earthwork and structural design for calculating the LT line was the activity carried out internally by the company, given that both had the same QT and only the CT of the internal activities was available for analysis. The design revision, carried out in parallel with the design addendum, followed the same selection criterion as the previous ones.

In the specific case of the school used for the development of the VSM, a difference of 129 business days was observed between the planned duration and the time required to complete the detailed design. According to reports from team leaders, most of the delays and challenges stem from the need for frequent revisions, which cause workflow interruptions (e.g. a non planned structural design and architectural design revision, which caused rework waste after the first manufacturing production). Additionally, buffers were required to mitigate the impacts of unpredictability in the deliveries of outsourced teams, which caused deviations from the initially planned duration.

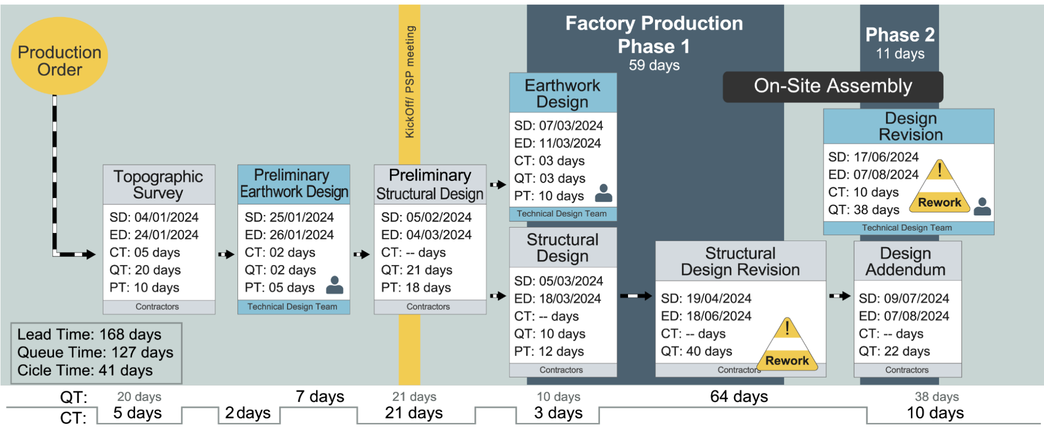

Figure 4: Current state of VSM - site stages connected to manufacturing

A recurring problem identified is premature client approval during the commercial phase, which occurs before a thorough assessment of the design based on the existing requirements. The pressure to finish the design as soon as possible often leads to completing this phase without checking all technical specifications, resulting in incomplete or underestimated information. Additionally, some activities (structural, earthworks, foundations) suffer from specification changes, disrupting manufacturing modules, increasing costs, and hindering team coordination. Delayed assessments, changes in client requirements, and adjustments to align the design with the actual site conditions and manufacturing plant status generate a cascade effect, requiring revisions in different work packages, contributing to increase design lead time. It was observed that the Production System Design (PSD) meeting was conducted when some detailed design decisions had already been made, leading to design rework and inconsistencies. To address this, the kick-off meeting should follow contract signing to define core requirements, while the PSP meeting should occur after soon initial project development.

For the future-state VSM (Figure 5), the PT adopted in the medium-term planning by the executive project leader were considered. It was observed that the CT never exceeded the planned duration when the work was performed by the company's internal team. One of the major challenges identified was managing commitments with outsourced contractors hired for specific services, which frequently contributed to delays and deviations from the schedule.

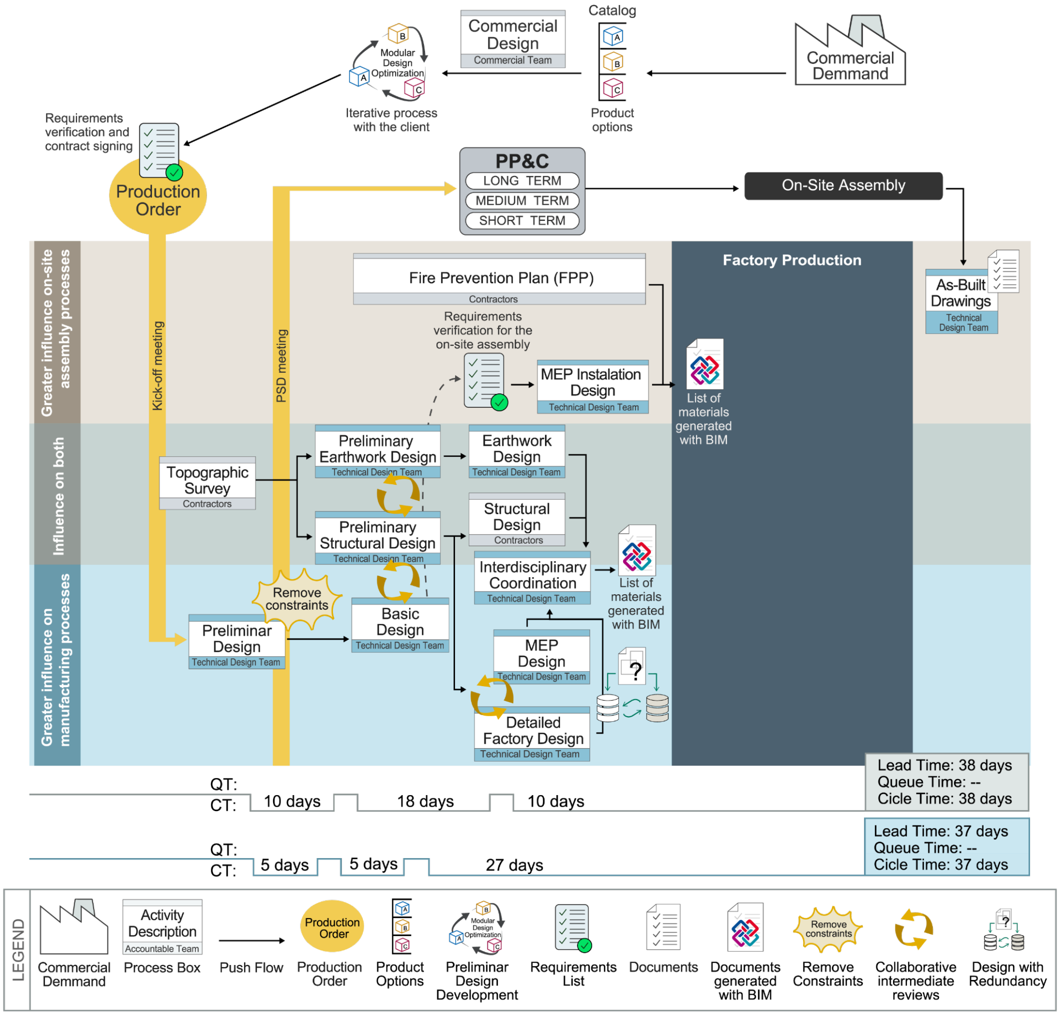

Figure 5: Future state VSM - improvement suggestions

These observations were corroborated by interviews with those responsible for detail design, who emphasized the need to implement a requirement-gathering protocol during the commercial phase. Such a measure would allow detailed design to be developed with less interference and fewer change requests, creating more stability in the process. The future state of VSM presented in Figure 5, suggest the following improvement opportunities:

- **Develop design alternatives:** By considering hierarchical modularity and standardizing interfaces between modules, it is possible to expand the range of standardized alternatives offered to clients and provide a greater variety of combinations. This contributes to increased efficiency, both in the development of design solutions and production.
- **Redundancies in product design:** Components should be designed in a way that allows for multiple alternatives, incorporating redundancies into the design so that modifications, if necessary, can be introduced in a controlled way without affecting design detailing. This provides flexibility to make adjustments in advanced project stages, which is strongly related to the set-based design approach.
- **Identification of information packages required at each design stage**: Each design participant must understand not only what is requested but also the level of detail and accuracy needed for the purpose at hand, given the transfer requests made by other team members, to make a reliable commitment. A major difficulty is to have clarity regarding how much work and what level of detailing should be delivered at each project stage, a challenge that needs to be addressed through frequent communication among different disciplines, always keeping the overall project value in mind.

- **Intermediate collaborative design reviews:** Some checkpoints must be implemented throughout the detailed design process, involving multidisciplinary teams to review and adjust the design frequently. This approach reduces unnecessary iterations, allowing effective revision planning. Additionally, it promotes process transparency and minimizes rework by allowing early alignment among those involved.

RESULTS AND DISCUSSION

The improvements proposed in the future VSM can potentially have a positive impact on reducing project LT, according to the analyses conducted. In the activity flow shown in Figure 3, the LT, initially calculated at 148 days, was projected to be reduced to 37 days, while in the flow presented in Figure 4, the forecast is a reduction from 168 days to 38 days. This estimated time reflects a reduction in waiting and queue times, as well as a potential improvement in the overall efficiency of review, alignment, and assessment activities.

The design flow has specific characteristics, such as frequent iterations, low repetitiveness, and progressive definition of means and goals (Wesz et al., 2018). Romero and Chávez (2011) highlight its ability to map overlapping flows. However, no recommendations are available for improvements or future-state map development. To represent this interdependence, three parallel lines were used, with two selected for comprehensive analysis.

Moreover, the need to incorporate a temporal dimension, a limitation pointed out by Erikshammar et al. (2013), was also observed in the case study, particularly in projects characterized by long cycles, frequent revisions, and creative iterations. Consequently, visual adaptations were made to the process boxes. Unlike the traditional VSM where all boxes are uniform, the boxes in this map were resized proportionally to the duration of the corresponding activities, including the waiting periods between them. This adjustment provides a more accurate temporal representation, enhancing the understanding of activity durations and the wastes incurred while waiting for information, and ultimately improving overall process visualization. In order to use the map to discuss improvement opportunities, it is crucial to understand the interactions between different domains and the coordination among multidisciplinary teams. A focused effort to enhance collaboration and process alignment across these areas may ultimately lead to more resilient and efficient MC processes.

Some propositions to eliminate waste and increase design efficiency are summarized in Table 2, focusing on reducing the work batches and continuous improvement:

Table 2: Proposed Strategies for Project Optimization in Modular Construction.

Points Analyzed	Suggested Tools/Practices	Supported Practice	Design Process	Product Develop.
Lack of client requirement capture and analysis	Professionals with expertise in capturing requirements and knowledge on the product to be delivered	Reduction of rework	X	X
	Formal approval flow before starting detailed design	Reduction of rework	X	
	Checklist to support assessment of document needs and specifications.	Continuous improvement	X	X
Lack of alignment between sectors	VSM to identify constraints and improve integration.	Cross-sector collaboration	X	
	Intermediate collaborative reviews to reduce rework and improve communication.	Cross-sector collaboration	X	
	Use of templates for collecting information on requirements	Transparency	X	X

Rework due to late changes	Adopt design redundancies to provide some degree of flexibility.	Reduction of rework		X
	Revise the planning of critical tasks to facilitate overall project flow.	Continuous improvement	X	
Lack of process standardization	Document existing procedures.	Transparency	X	X
	Hierarchical modularity to explore repetitive activities and improve interoperability	Continuous improvement		X
Delays caused by outsourced teams	Planned buffers in schedules to mitigate impacts of unforeseen events	Predictability	X	
	Make constraints explicit.	Transparency	X	
Inadequate coordination of inter-dependent activities	Reduction of unnecessary design iteration.	Reduction of rework	X	X
	Workload leveling to balance volumes and reduce waiting times.	Process efficiency	X	
	Use a matrix of design status to monitor work-in-progress and reorganize workflows.	Transparency	X	
	Resequencing and regrouping design tasks to reduce complexity.	Continuous improvement	X	

CONCLUSIONS

This study provided evidences that VSM is an effective tool for addressing problems related to complexity in MC design processes. By identifying waste, reducing rework, and improving cross-sector alignment, the proposed improvement achieved a potential 75% and 77% reduction in LT. These results highlight the potential of Lean principles to enhance integration between disciplines, minimize the impacts of variability, and foster resilience in dynamic project environments.

The main contributions of this investigation are concerned with understanding MC design management challenges and providing actionable strategies to deal with complexity. Although the implementation of improvements remains context-dependent, this study has emphasized the importance of balancing standardization with flexibility, making information flows systematic, as well as enhancing multidisciplinary collaboration as a means to address the inherent complexity of the design process.

Future work should explore the application of VSM in diverse MC contexts, prioritize Lean tools across product development phases, and assess long-term impacts on manufacturing and site assembly performance. This approach will further advance the sector's ability to manage complexity while promoting continuous improvement. The final results of implementing the guidelines—including impacts on timelines and rework—will be explored in future publications.

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