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MODEL FOR PRODUCTION SYSTEM DESIGN IN MODULAR CONSTRUCTION PROJECTS

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ABSTRACT

Modular construction has gained increasing relevance as a kind of Engineer-to-order (ETO) industrialized building systems, which are plagued by different sources of complexity. Production system design (PSD) is one of the core activities in production management, translating the intended production strategy into a set of decisions to improve flows. Previous research efforts were mostly limited to the design of production systems for projects that involved traditional construction technologies. However, the scope of PSP decisions tends to be broader in industrialized building systems because it requires information from multiple production units to align strategic and operational decisions. The aim of this research is to devise a process model for designing production systems for ETO industrialized building systems within the context of modular construction. Design Science Research was the methodological approach adopted in this investigation, which involved three empirical studies carried out in partnership with a company that delivers modular construction projects. The main outcome of this investigation is a set of decision-making steps to support the design of the production system based on core operations management concepts and principles. The main benefit of this model to guide the development of PSD in a systematic and formalized way.

KEYWORDS

Lean construction, Production system design, Engineer-to-order, Modular Construction, 4D BIM.

INTRODUCTION

Construction is essentially the design and installation of components and sub-systems in which processes have many interdependent interfaces and a high level of complexity (Ballard and Howell, 1998). Adapting and re-engineering site-intensive construction processes by adopting industrialized building systems offers some advantages in terms of the resources required, energy consumption, and environmental issues compared to conventional construction methods (Nabi and El-adaway, 2020).

The choice of offsite prefabricated building systems brings technical and organizational implications for site-installation and more pre-construction planning, compared to traditional technologies (Voordijk et al., 2006). However, the degree of off-site production generally varies, from the prefabrication of non-volumetric elements that are assembled on-site to the highest degree of prefabrication known as modular construction.

Modular construction has been defined as the use of panelized elements or volumetric units that are manufactured under controlled conditions in factories with finishing and technical

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systems sometimes already integrated and then transported to the site for installation (Gibb, 2001; Innella et al., 2019). The adoption of modular construction has increasing relevance within the Engineer-to-order (ETO) industrialized building systems (Pero et al., 2015).

In this context, the relevance of operations management strategies that support product customization increases as customers' demands and expectations for specific solutions grow (Johnsen and Hvam, 2019). ETO production systems can be defined as one 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).

Projects that deliver ETO industrialized building systems can usually be regarded as complex sociotechnical systems (Saurin, 2017). It is formed by a network of technical (e.g., manufacturing plants, construction sites, etc.) and social elements (e.g., assembly teams, customers, managers, etc.) that are interconnected and dynamically interact (Koskela, 2000). Consequently, this environment is plagued by different sources of variability, which can be removed to some extent. According to Cannas and Gosling (2021), little attention has been given to how to deal with the remaining variability.

Production system design (PSD) is a pre-construction planning process involving decisions that play an important role in implementing core Lean concepts to minimize the effect of variability (Koskela and Ballard, 2004). PSD is concerned with the development of operation and process design in alignment with product design, the structure of supply chains, and the allocation of resources (Ballard et al., 2001). It translates strategic objectives into design and implementation actions at the operational level (Cochran, 1999). Production systems should be designed to be capable of meeting demand (Alves et al., 2006), affecting product delivery time, waste elimination, and value generation (Koskela and Ballard, 2004). The main outcome of PSD is to create appropriate conditions for subsequent decision-making (Ballard et al., 2001) and should be evaluated and revised in the course of a project as a dynamic process (Tsao et al., 2005).

Previous research has devoted efforts to define design parameters and guide PSD through a step-by-step process (Ballard et al., 2001; Tsao et al., 2005; Theis et al., 2017; Frandson, 2019), most of them limited to the context of traditional construction methods. Despite its relevance and impact on production planning and control, PSD is often neglected: there is no formal process, nor are its results made explicit (Ballard et al., 2001; Schramm et al., 2006; Barth et al., 2020). Moreover, very few studies explored prescriptive abstract knowledge related to the development of PSD for the context of ETO industrialized building systems. More specifically in the case of modular construction, there is still a lack of understanding on how to plan and coordinate modular construction projects (Lim et al., 2022). The scope of decisions in this context is broader than in traditional construction, because it requires information from multiple production units (e.g. manufacturing plants, construction sites) to align strategic and operational decisions.

The aim of this research lies in proposing a process model for designing production systems for ETO industrialized building systems within the context of modular construction. One of the main contributions of this investigation is establishing connections between different PSD decision categories with design principles for planning and controlling ETO industrialized building systems, proposed in the literature.

LITERATURE REVIEW

PRODUCTION SYSTEM DESIGN AND RELATED CORE PRODUCTION CONCEPTS

PSD involves several decision categories which are interdependent, such as the definition of work zones, batch sizes, sequence of activities, process rhythm, layout definition, and allocation of buffers (Ballard et al., 2001a; Schramm et al., 2004; Alves et al., 2006; Frandson et al., 2015; Barth et al., 2020).

One of the most important decisions in PSD is the definition of flows (Schramm et al., 2004). This decision can be made by adopting location-based planning and control methods, which explicitly emphasize planning for flow and explore the location as an intrinsic component of construction plans (Kenley and Seppänen, 2010; Sacks et al., 2017; Olivieri et al., 2019). A project can be broken down into a location breakdown structure (LBS), which defines zones in different hierarchical levels: those locations are used to plan and control work, i.e., physical locations are explicitly used to define where work needs to be done (Kenley and Seppänen, 2010). Those methods can contribute to improving planning reliability, assisting in levelling workflow (Nutt et al., 2020), analysing space constraints (Hamzeh et al., 2012), and allocating buffers (Kenley and Seppänen, 2010).

Much variability exists in resource flows, and the probability of missing inputs is therefore considerable (Koskela, 2000). In construction, the concept of buffer is widely used, being a well-known mechanism to protect processes against variation and resource starvation (Alves et al., 2006; Poshdar et al., 2015). Ballard et al. (2020) argue that buffer management is conceived to deal with variability statistically described in advance. However, when uncertainty is hard to anticipate and quantify, slack plays a key role by supporting resilient performance with a broader range of strategies to deal with unexpected events (Fireman et al., 2022). Slack can be used to manage both product and operations flow, being particularly relevant in the context of ETO industrialized building systems (Bataglin et al., 2022).

In addition to the concept of product modularity, which play a key role in Modular Construction, the adoption of small batches in location-based planning and control allows the application of the concept of process modularity, which means breaking down the process into standard sub-processes (Gualandris and Kalchschmidt, 2013). The division of the project into either product or process modules can create a certain degree of process repetitiveness even though some projects have limited repetition (Koskela, 2000). Therefore, process modularity can be adapted to be used in PSD, for defining the batch size and the project execution strategy, as suggested by Schramm et al. (2004) and Ballard et al. (2007).

Improvements in the quality of the input information can positively affect the quality of the planning and control outcomes (Gledson and Greenwood, 2017). Building Information Modelling (BIM) can be used to improve the quality of building design information and to establish mechanisms and procedures by which information is communicated and shared among project team members (Crotty, 2012). Moreover, four-dimensional (4D) BIM can be used to visualize and simulate production and logistics processes, in order to support decision making in PSD (Crowther and Ajayi, 2019).

RESEARCH METHOD

Design Science Research (DSR) was the methodological approach adopted in this investigation. This approach aims to produce innovative solution concepts (artifacts) intended to solve a class of problems faced in the real world and provide a prescriptive theoretical contribution (Lukka, 2003). In this research work, the artifact is a process model for designing production systems for ETO industrialized building systems within the context of modular construction.

This investigation was developed in close collaboration with a company that delivers modular construction projects in Brazil. In most contracts, this company delivers projects as complete solutions, acting as a contractor that develops design, produces prefabricated modules in manufacturing plants, transports modules to the construction site, and carries out site installation, which combines the assembly of volumetric and non-volumetric prefabricated components, and the execution of some traditional site construction activities. The criteria for choosing this company were: (a) there was an ongoing improvement program based on the Lean

Production approach, and (b) its projects involved ETO industrialized building systems, including components and processes with different levels of industrialization. The main characteristics of the construction projects was summarized in Table 1. Due to the research strategy adopted, there was a strong interaction between the companies' staff and the research team in the development of the artifact, including learning and reflection cycles that were necessary for its refinement.

Table 1: Characteristics of each project.

Characterization criteria	Construction projects		
	A	B	C
Project type	Expansion of an operating prison consisting of cells and supporting spaces	Construction of a new prison consisting of cells and supporting spaces	Multi-family residential of thirty apartments
Area	15,000 m²	23,500 m²	5,200 m²
Planned duration	12 months with a partial delivery at 6 months	12 months with a partial delivery at 6 months	30 months
Main construction technologies	Heavy reinforced concrete modules for the cell, prefabricated concrete panels for the collective living spaces, cast-in-place concrete walls for the administration and control spaces	Heavy reinforced concrete modules for the cell, prefabricated concrete panels for the collective living spaces, lightweight concrete modules for administration, assistance, and control spaces	Cast-in-place concrete structure for underground garages, stair towers, and leisure areas, customized lightweight modules for apartments
Stages of the project being carried out during the analysis	Design, prefabrication, logistics, and construction	Design, prefabrication, logistics, and construction	Design and construction of a prototype

The research process was divided into three phases:

(i) understanding the practical problem, based on the analysis of all project stages and discussion of the construction project premises. The perspective of each department was considered in this initial analysis, as well as requirements from the clients. Those premises included the following information: a) project milestones and contractual terms – start date, partial deliveries, payments; b) identification of the level of customization, i.e. expected client change orders; c) constraints of the workday and access to the construction site – managers' team, workers and suppliers' deliveries; d) design and manufacturing plants interdependences – production cycle time for different types of products (e.g., heavy reinforced concrete modules for the cell, prefabricated concrete panels for the collective living spaces) at the manufacturing plant; e) logistics analysis – load plans and the design of different types of loads; and f) critical suppliers and subcontractor in light of the lead time. This set of information was the starting point for the PSD formalization; **(ii)** development phase focused on defining production strategies to integrate the construction site and manufacturing plants, starting with the PSD development for projects A and B which took two months, and later the PSD for project B which took four months. Synchro PRO (version 6.5.1.5) was the software package for devising 4D models; and **(iii)** assessing the artefact and reflecting on the practical and theoretical implications of this investigation.

Multiple sources of evidence in this investigation, including semi-structured interviews with representatives of different departments (design, production, logistics, contracts, purchasing, and planning), direct observation of manufacturing and construction processes, and participant observation in planning and control meetings, and assessment workshops, summing up 102 hours of data collection.

FINDINGS

MODEL FOR PRODUCTION SYSTEM DESIGN

Figure 6 presents the proposed process model for designing production systems for ETO industrialized building systems within the context of modular construction. This process model has a set of decision-making steps and elements that are directly associated to a set of core concepts and principles. In following sections, the PSD step-by-step is explained, including its main elements and decision-making steps.

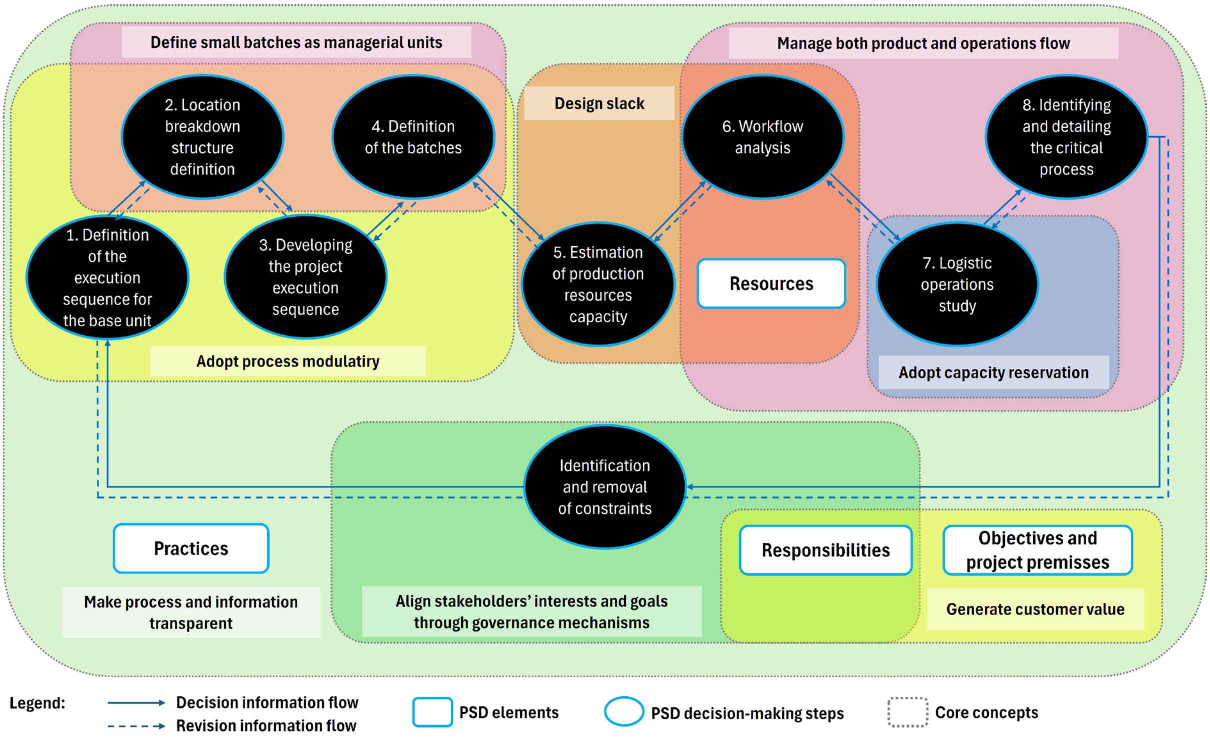


Figure 1. PSD process model and core concepts and principles involved.

Projects A and B

The production system design was devised concurrently with the product design stage, in both projects A and B. Although there several pre-designed standard modules were used in both projects, in which some components and interfaces had been previously defined, adjustments for the context of each project were necessary to meet client requirements and land-specific constraints, such as the ones related to earthwork and foundations.

The first step consisted of the **analysis and definition of the execution sequence for the base unit**. In both projects, each construction technology had a specific sequence of on-site activities, and the interdependence between them was analysed by using activity precedence diagrams. The following step consisted of **defining the location breakdown structure**, which had different hierarchical levels (Figure 1). In the first level the division into zones was based on the construction technologies used. The LBS second level was named "MOD", according to the terminology adopted in the architectural design. It represents an area of the building formed by a mix of construction technologies, defined in both projects as the base unit. For example, project A – MOD 1 was an area that combined heavy reinforced concrete modules, prefabricated concrete panels, and cast-in-place concrete walls; project B – MOD 21 was designed for health assistance and had only of lightweight concrete modules.

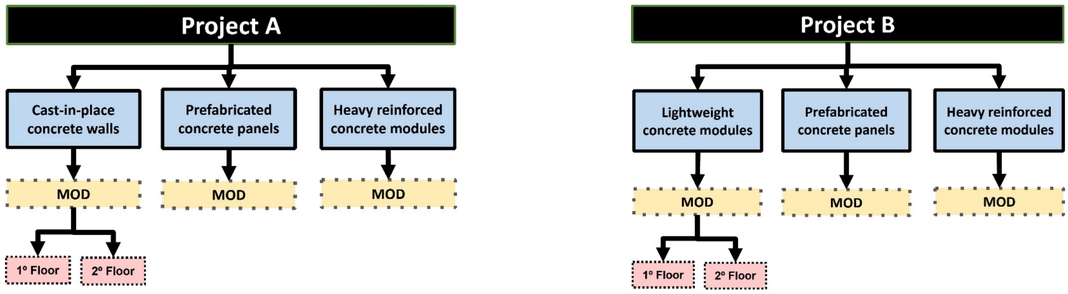
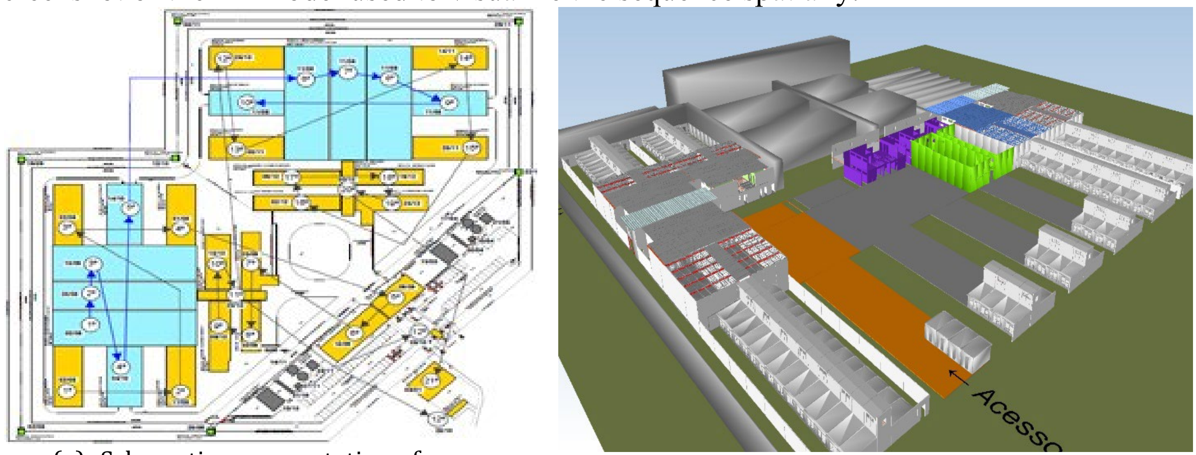


Figure 2. Location breakdown structures.

The third PSD step was **developing the project execution strategy** through the definition of the main work and product flows. In the empirical studies, this was developed for activities that involved the delivery and assembly of prefabricated elements and their interfaces. This analysis was supported by visualization tools which facilitate the understanding of the execution strategy and the interdependence between different activities. Figure 2 (a) shows a simplest representation using 2D drawings and arrows to indicate the path. Figure 2 (b) is a screenshot of the 4D model used to visualize the sequence spatially.



(a) Schematic representation of trajectories (source: the company)

(b) 4D BIM simulation screenshot

Figure 3. Example of tools adopted to support trajectory analysis.

After the definition of the project execution strategy, the **definition of production and transfer batches** and the **estimation of production resources capacity** (definition of cycle times, number of workers, and equipment) were carried out. Subsequently, the line of balance (LOB) was produced as a visual device to support team discussions, and the following decisions were made: (a) production rhythm and cycle time for a set of processes; (b) the workflows of the main crews; (c) identification of interferences and interdependence between different processes; (d) time buffers needed between processes; (e) a definition of the period of site assemble that required cranes; and (f) the beginning and conclusion dates for each process. During this analysis, an effort was made to maintain, as much as possible, a continuous flow of materials and products and an uninterrupted flow of crews. The estimation of production resource capacity was revised after this step.

Figure 3 represents an excerpt of the LOB of projects B. As described previously, in Project B there were some building areas for assistance, such as the kitchen, laundry, and workshop, which did not have a repetitive character. Consequently, due to the preference of the company to plan the activities considering the second level of the LBS (building areas defined in the architectural design as “MOD”), the size of the batches was not the same for all zones.

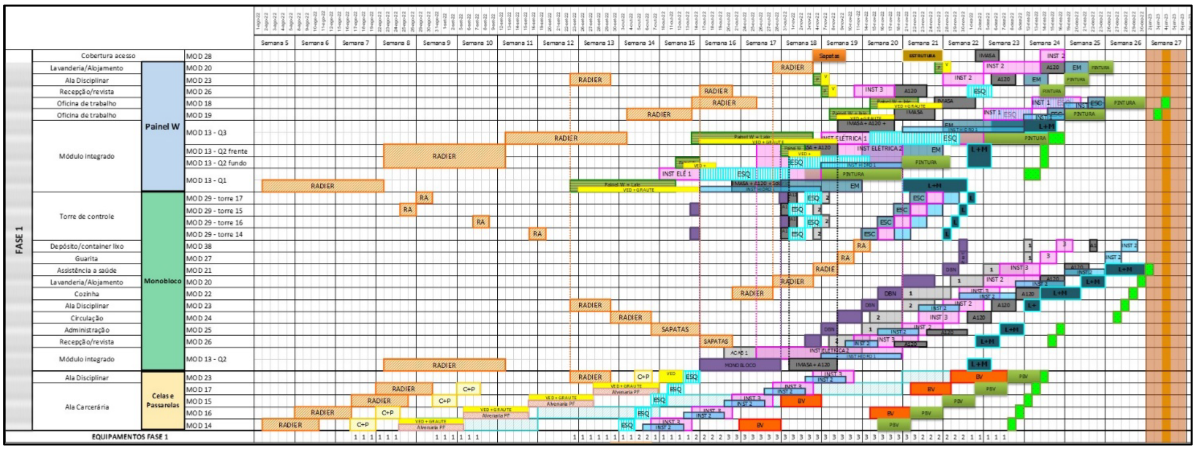


Figure 4. Excerpt of the line of balance Project B.

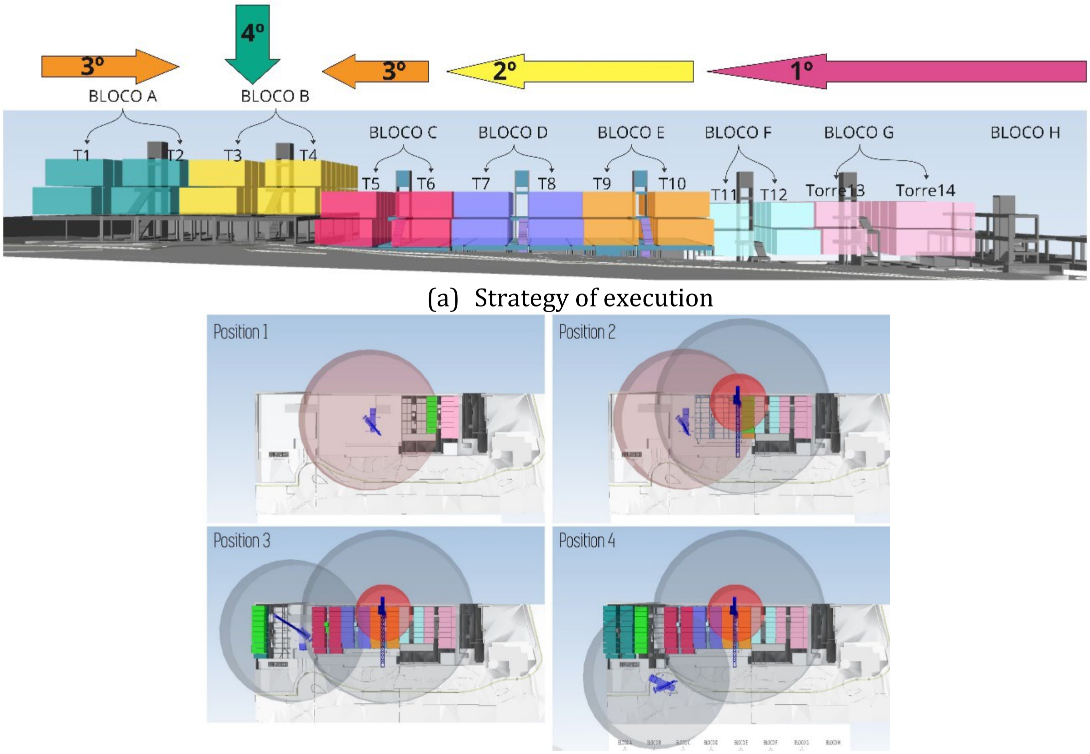
Projects C

The PSD was devised along the development of the detail design. This enabled decisions in the product detail design to take into account site installation processes with the aim of improving the production system's performance. The **identification and removal of constraints** was a routine added from the beginning of PSD, similar to the look-ahead planning level of the Last Planner System. Different categories of constraints were identified, considering decisions and their influences on the execution sequence, such as design, plant production, procurement, resources, etc.

The starting point for PSD development was the **analysis and definition of the execution sequence for the base unit.** Precedence diagrams were developed to understand the relationship between activities considering the technical constraints of each construction technology. This analysis contributed to the **LBS definition**. At the first level, the project was divided according to the construction technology – mixed and cast-in-situ blocks. The mixed block comprised two apartment towers, a tower of circulation, and a level of garages, representing the second level of the LBS. At the third level, the smallest repetition unit was represented by the apartment unit and levels for the cast-in-situ zones. The apartment unit was defined as the main unit of control, considering that a high degree of customization was allowed to customers.

Regarding the construction site, there were severe constraints on workspace and access, mainly due to the need for parking areas excavation at underground levels. Moreover, there was only one vehicle entry. In this case, the analysis of internal logistics operations was essential to define the production execution strategy. Figure 4 (a) represents the execution sequence, considering the cranes' positioning and turning radius for module assembly, which are shown in Figure 4 (b). The **definition of the production and transfer batches** and the **estimation of production resources capacity** (definition of cycle times, number of workers, and equipment) were established after the execution strategy development. The aim was to define small production batches, to have some process repetitiveness, following the process modularity concept. After that, the LOB was produced (Figure 5), based on the analysis of **work- and product-flows,** with the aim of synchronizing processes, to achieve to some extend a continuous flow of products and an uninterrupted flow of crews. A 4D BIM model (e.g., Figure 4) was also used for simulating scenarios and supporting decision-making during the discussions.

As customers were allowed to choose an apartment's internal layout, a deadline for change requests (Figure 5 – green circle) was established, i.e. the deadline for clients to request changes in apartment units, so that these do not have a substantial impact in the supply of resources and, consequently, in site installation.



(a) Strategy of execution

(b) Cranes positions according to the assembly sequence

Figure 5. Project execution strategy and internal logistic study.

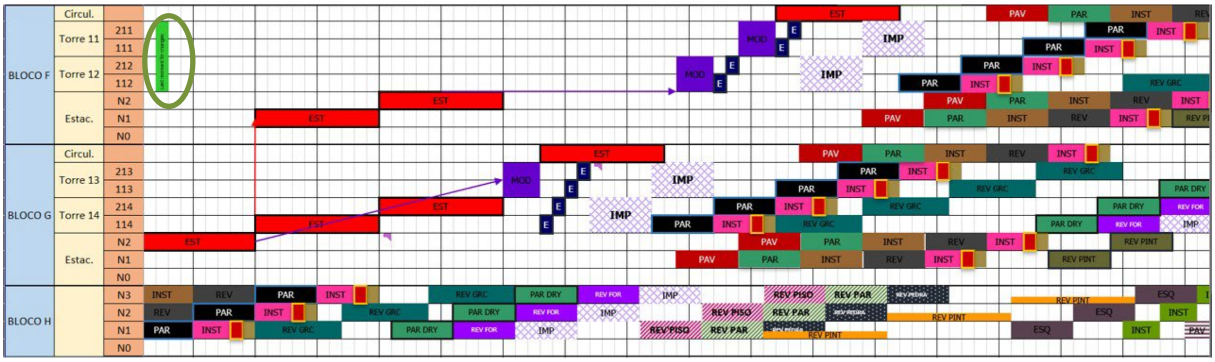


Figure 6. Excerpt of the LOB.

DISCUSSIONS

There were substantial differences between the first two project (A and B) and project C in terms of construction technologies, and type of contract. This is a challenge for establishing a highly standardized PSD process. By contrast, in all empirical studies, the company had the opportunity to develop in parallel with the product design. This enabled the consideration of production requirements in design, especially regarding the interface between different construction technologies. It also facilitates the consideration of some customers' requirements, contributing to improve value generation, as suggested by Schramm et al. (2006). In project C, for example, confirmation points for customers to make decisions and changes were established in order to allow time for deliveries from suppliers, similar to the customer order decoupling point proposed by Formoso et al. (2022).

Most of the ETO companies, such as the company involved in this research study, work in a multi-project environment in which some of the resources are shared between different projects (e.g., design team, assembly crews, manufacturing plants, etc.). It requires the participation of representatives from design, manufacturing plants, and logistics departments in PSD decisions, expanding decisions beyond site installation. Consequently, the stakeholders' interests and goals alignment, in this case also from different production stages, demands well-established responsibilities. An important example in this discussion is the load plans, which play the role of an integrative tool between manufacturing and site installation, i.e., each production stage (manufacturing plant and expedition) has well-defined responsibilities in order to meet demands from construction sites.

The step of identification and removal of constraints was suggested along the implementation of the model, to encourage the establishment of commitments (e.g., design deliverables, material supplies, etc.) before the construction stage begins. In this investigation, some decision-making steps were undertaken earlier as part of PSD due to the overlapping between the production stages, making the project lead time shorter than traditional construction projects.

Regarding the logistics operation study added to the PSD model, it enabled to manage both product and operations flow. It must be split into two sets of tasks, as suggested by Bataglin et al., (2020): i) internal logistics by planning the site layout and the flows involved in the transportation, storage, and assembly of components, and ii) external logistics by using confirmation points for pulling the off-site production of components and their delivery to the construction site. The daily assembly batch detailing influences decisions regarding external logistics and contributes to controlling the flow of components and synchronizing production in both the manufacturing plant and construction site. Even in non-repetitive projects, such as Project B, there is some degree of process repetition, so short learning cycles must be adopted to facilitate control. Thus, there is a need to carry out a careful definition of the content of the small batches adopted, when there is not a repetitive unit naturally defined (e.g., an apartment, or a floor).

Some types of slack were explicitly planned in all empirical studies, directly related to production flow: a) consideration of the weekend as a time buffer in case the activities scheduled for the week have not been completed, b) underloading the resources to absorb variability and unpredictability in production, so, the workers have time to react and complete the work in a specific zone; c) backlog of work packages in the short-term plan to be carried out if the execution of the initially planned work packages is delayed or suspended; d) equipment leased to perform a specific activity (e.g., the groundwork for floating slab) being used to meet the demand of another activity (e.g.; drainage excavation) which was using an equipment that had broken down; and f) planning two-weeks in advance in the short-term plan for the assembly activities directly connected to the prefabrication stage such as assembly of components and modules, in order to have additional confirmation points for delivery.

The different tools and methods used during PSD made the design of the production system more transparent. Different types of plans were combined, representing functional models that bring diverse perspectives - e.g. information available is a spreadsheet and also a graphic representation of a plan placed on the construction office wall – this can also be considered an instantiation of slack. The visual tools (e.g., Figure 2, Figure 4, and Figure 5) and the information produced in the PSD must support decision-making during production planning and control routines, making it more reliable by increasing process transparency and developing a common understanding of the production strategy, as suggested by Frandson (2019). For example, the 4D BIM model gather information about the product and processes and contribute to increase the reliability of the information shared between stakeholders.

Participant observation in planning meetings and discussions with managers and representatives of different departments involved in the process (design, production, logistics, contracts, purchasing, and planning) provided evidence that the company became interested in incorporating some elements of the proposed process model into the existing managerial system.

In fact, after that investigation, the company started to develop PSD for all projects, using most tools and methods proposed in this research work. It was also observed that the formalization and the outcomes of the PSD contributed directly to increasing the effectiveness of different production planning and control levels and that the dissemination of information among stakeholders by using visual devices was improved.

CONCLUSIONS

The main outcome of this investigation is a process model for designing production systems for ETO industrialized building systems within the context of modular construction. The solution concept is formed by a set of decision-making steps and main elements to support the design of the production system based on core operations management concepts and principles, addressing the need to make the PSD process systematic and formalized. The starting point for the solution development was a set of decision categories based on the literature review (Ballard et al., 2001; Schramm et al., 2004), which was then adapted to the context of modular construction, based on the development of three empirical studies.

ETO industrialized building systems are plagued by different sources of complexity, associated with the diversity of interdependent processes, including design and production flows, and short lead time. Production system design is a way to deal with complexity by expediting decisions and anticipating some impacts that may affect the operation of production systems. The collaborative development of PSD allows the upstream production stages such as design, prefabrication, and logistics to consider the need to manage production flows and to establish triggers from site installation.

From a theoretical perspective, this research work has contributed to the understanding of core concepts and principles that are addressed by the implementation of PSD, and also of the information demands of the PSD process, considering the context of ETO modular construction systems. The proposed process model (Figure 6) represents a way to systematize the underlying concepts and connect them with the decision-making steps and elements of the PSD process. The work adopts some core ideas of Lean Construction such as managing flows, reducing variability and increasing process transparency, in order to create basic stability in the production system. The concept of process modularity explored in this investigation, referring to how the different site assembly activities are sequenced and grouped to achieve repetitiveness, can be closely aligned with the flow view and contributes to managing complex systems.

Regarding the limitations of this investigation, despite exploring the different construction technologies produced by the company, the three empirical studies were carried out in a single company. Therefore, it is necessary to further refine the proposed process model, by implementing and improving it in other contexts. It must be pointed out that the artifact emerged at the end of the development phase and has not been fully assessed in terms of utility and applicability. Then, evaluating and assessing their utility, expanding the set of related concepts, is another suggestion for further research.

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