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THE PICO FRAMEWORK FOR ANALYSIS AND DESIGN OF PRODUCTION SYSTEMS FOR CONSTRUCTION

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ABSTRACT

PICO is a framework that provides a conceptual guide for production system analysis and design in the construction industry. It has four key components: Production control mechanism, Information and communication system, Commercial terms, and Organizational structure. Each component is highly interdependent and has a set of detailed parameters and enumerated values. A comprehensive literature review, case studies, and analysis highlighted the knowledge gaps in current production system design frameworks. The PICO framework was originally devised to design a production system suited for short-takt production in residential construction, but it has been developed into a comprehensive mapping tool for the design and analysis of construction production systems in general. The paper shows an application of the framework to a takt system as a case study and an example of its application. The framework expands the current understanding of production systems in construction, offering new insights and a comprehensive approach to designing new production systems.

KEYWORDS

Production system design, Production planning, and control, Residential Construction, Integrated Project Delivery (IPD), Transformation-Flow-Value (TFV).

INTRODUCTION

Production systems consume inputs (people's work, capital, information, equipment, materials) to produce goods and services by integrating physical and information flows constrained by capacity and other limitations (Nahmias and Cheng 2009). The Lean construction community has long advocated for greater control over operational flows in the production system to reduce waste and improve efficiency (Wandahl et al. 2021).

Current understandings of production systems in construction rely on the Transformation, Flow, Value (TFV) theory (Ballard et al. 2001; Koskela 2000) and the Lean Project Delivery (LPD) approach ("Lean Project Delivery" 2023). The TFV theory proposes that its three concepts should be integrated and balanced to optimize the production system. The theory

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serves as a tool for conceptualizing production system performance, supporting efforts to identify and eliminate waste (Bølviken et al. 2014). While TFV is useful in detecting waste within the production system, it does not provide a structured framework to identify and configure production systems systematically. The LPD project management approach strives to enhance flow and diminish waste ("Lean Project Delivery" 2023) through the presentation of principles that can be implemented in various forms.

The PICO framework presented here is a tool for applying the LPD methodology through use of a set of detailed parameters based on TFV theory. The framework provides a detailed view of the existing decision variables involved in designing a production system in construction. In the current era, with various lean methods available, the PICO system offers a comprehensive approach that allows the designer of a production system to characterize the way to achieve LPD goals. The framework aims to define the interrelationships between production system components comprehensively and holistically. We first present the background and research methodology, followed by the PICO framework and a case study demonstrating the framework's application in a residential project in Finland.

BACKGROUND

The PICO framework supports the development of production systems within the construction industry while aiming to bridge the current knowledge gaps. Implementing lean construction methods marked a significant shift in the language of production within the construction industry, affording managers a fresh perspective on the production system. However, while several theoretical frameworks such as TFV and LPD were developed in this regard, they lacked the necessary level of detail and did not furnish operational tools for applying the principles (Ballard et al. 2001). Consequently, any stakeholders tasked with providing solutions to pertinent issues were left wanting information on the mutual effects and available possibilities. Furthermore, the industry's attitudes toward technology and its role in production have not changed significantly over the past two decades. This chapter thus presents the historical backdrop of the construction production system theories upon which the current production systems are built and present the knowledge gap the PICO framework aims to bridge.

HISTORICAL OVERVIEW

The history of the design of production systems in construction can be traced back to the early 20th century when the construction industry started adopting industrial production principles to increase efficiency and improve productivity. This was exemplified by the use of assembly line techniques in constructing skyscrapers in the US in the 1920s and 1930s, which allowed for the efficient and coordinated construction of large-scale buildings (Sacks and Partouche 2010; Ward and Zunz 1992). In the 1950s and 1960s, the industry embraced advanced production techniques such as prefabrication and modularization to manufacture building components off-site and reduce construction time (Hashemi 2013). In the 1970s and 1980s, construction researchers and practitioners developed formalized models and frameworks, including the influential Construction Industry Institute's (CII) "Research Team" model (Tucker 2007).

In the 1990s and 2000s, the construction industry continued to evolve, and production system design became increasingly important as global competition increased and the need for cost-effective, high-quality construction solutions became more pressing. In response to this, researchers and practitioners developed several new models and frameworks, such as the Integrated Project Delivery model (IPD)("Integrated Project Delivery: A Guide" 2007). These models emphasized the importance of collaboration, communication, and integration to achieve optimal project outcomes.

LEAN PRODUCTION SYSTEM

Lean construction production methods and systems are increasingly popular in academic and research settings due to their proven ability to enhance productivity (Howell and Ballard 1998; Thomas et al. 2002; Wong 2018). In the construction industry, production systems refer to the methods and techniques used to organize and manage the various processes involved in construction projects (Ballard and Howell 1998). Koskela (2000), offered a lean theory of production, conceptualizing it through the lens of the Transformation, Flow, and Value (TFV) views. The TFV approach highlights the importance of maximizing value, minimizing waste, and efficiently producing the product. Transformation focuses on converting inputs to outputs. Flow considers the flows of materials, resources, information, and products through space and time, and the Value pertains to methods for capturing requirements and achieving quality in the eyes of the consumer. Ballard et al. 2001 proposed a set of business objectives for project-based producers based on the TFV theory, which instructed adopters to "Align stakeholder interests" or "Reduce variability", for example. These guidelines provide a valuable decision-making framework covering various global organization production aspects.

Subsequently, it was recognized that incorporating changes during production without considering the integration between stakeholders in the production process was a challenging task. The IPD contract method was developed to address this issue ("Integrated Project Delivery: A Guide" 2007). It is a collaborative project delivery approach that involves the owner, designer, and builder working together as a team from the early stages of a project to achieve project goals, such as reducing waste, improving quality, increasing efficiency, and maximizing value. IPD is based on a shared risk-and-reward contract that promotes collaboration and communication among team members. The primary objective of IPD is to create an integrated and efficient project delivery process that benefits all stakeholders.

Mossman (2010) introduced a model with three domains that apply to every construction project, as illustrated in Figure 1. This production system design model emphasizes the critical need to consider and align the commercial terms, operating systems and organizational structures to implement the Lean Project Delivery approach ("Lean Project Delivery," 2023). A lean project's success depends on effectively integrating the elements of these domains.

Figure 1: Production system design in construction (Mossman et al. 2010, p.10)

The organizational domain involves the integration of the owner, designer, and contractor. The operating system refers to the implementation of production control methods and tools, such as the Last Planner System (LPS), Value Stream Mapping (VSM), and Building Information Modelling (BIM), and the commercial terms pertain to the incentives of the various stakeholders, such as the traditional Design-Bid-Build (DBB) model prevalent in the industry, Design-Build (DB), Collective Risk Management, and Profit and Loss Sharing.

These theories and frameworks present objectives and low-resolution production system design guidelines. There is no comprehensive tool that categorizes and clusters the variables of each domain to offer a holistic understanding of the interdependence of every decision made. The theories presented in the literature lack a comprehensive framework that can be practically applied to an operative production system and an understanding of the interconnectedness within the system.

RESEARCH AIM AND METHODS

The aim of this work was to devise a new conceptual framework for production system design that considers all aspects of the project, including people, methods, means, economics, motivations, and the interactions among them.

We employed a two-cycle methodology (Figure 2) following the iterative improvement principle of design science research (Hevner 2007). The first is the Explore cycle, and it comprises three iterative steps: 1) qualitative analysis of the literature and previous studies on construction production systems, 2) observing current production systems from case study projects in literature and other self-collected projects, and 3) examining the current paradigm of production system design through the findings from the first two steps. The second is the Elaborate cycle, in which we consolidate the learnings from the Explore cycle to arrive at a coherent and holistic production system design framework. The three steps within this cycle are 1) devising a list of production system design parameters, 2) validating the framework through case studies, which involved site visits, interviews with project managers and foremen, and workshops with senior management of the construction company, and 3) co-creating production system design concepts through discussions with the construction company.

In the following sections, we present our proposed conceptual framework, explaining each component in detail. Then, we apply this framework to a case study residential project in Finland to demonstrate how it can contribute to the analysis and improvement of the production system design.

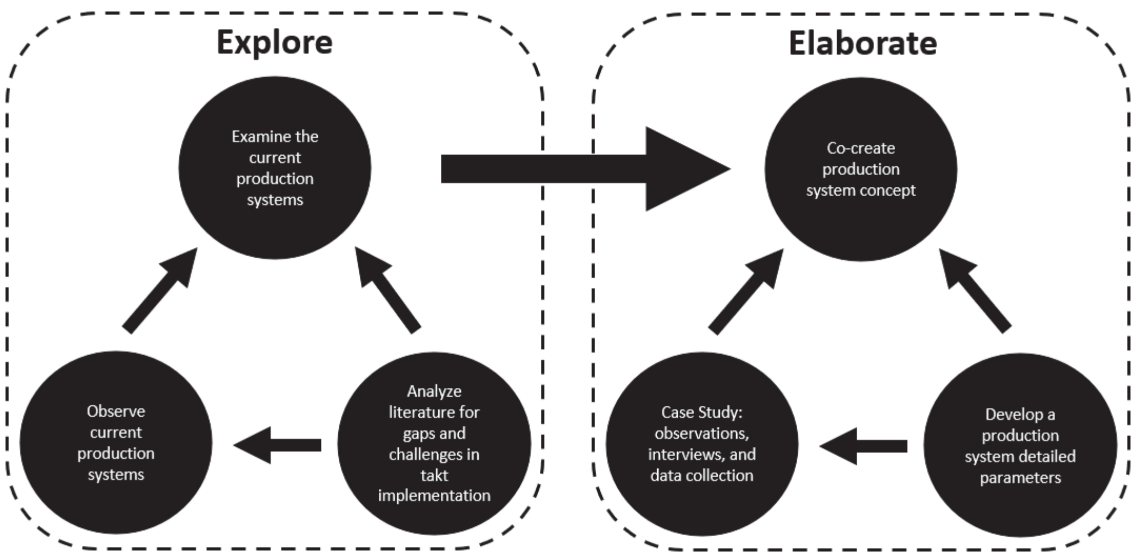

Figure 2: Research methodology (adapted from Hare et al. 2018).

A NEW CONCEPTUAL FRAMEWORK

To address construction projects' complexities and their dynamic nature, we propose a new conceptual framework for production systems that considers all aspects, including people, methods, means, economics, motivations, and their interactions. The framework, designated with the acronym 'PICO', consists of four components: (P) Production Control Mechanisms, (I) Information and Communication Systems, (C) Commercial Terms, and (O) Organizational Structures, presented in Figure 3. The full PICO framework is defined in an Excel worksheet that provides a detailed breakdown of the parameters relating to each part of the production system, descriptions and a set of possible values for each parameter. This tool serves as a map of decision variables in the design of a production system for construction. Through this approach, we can identify underlying issues and develop solutions that consider the interconnectedness of the production system. The framework considers adoption of lean principles and new monitoring technologies.

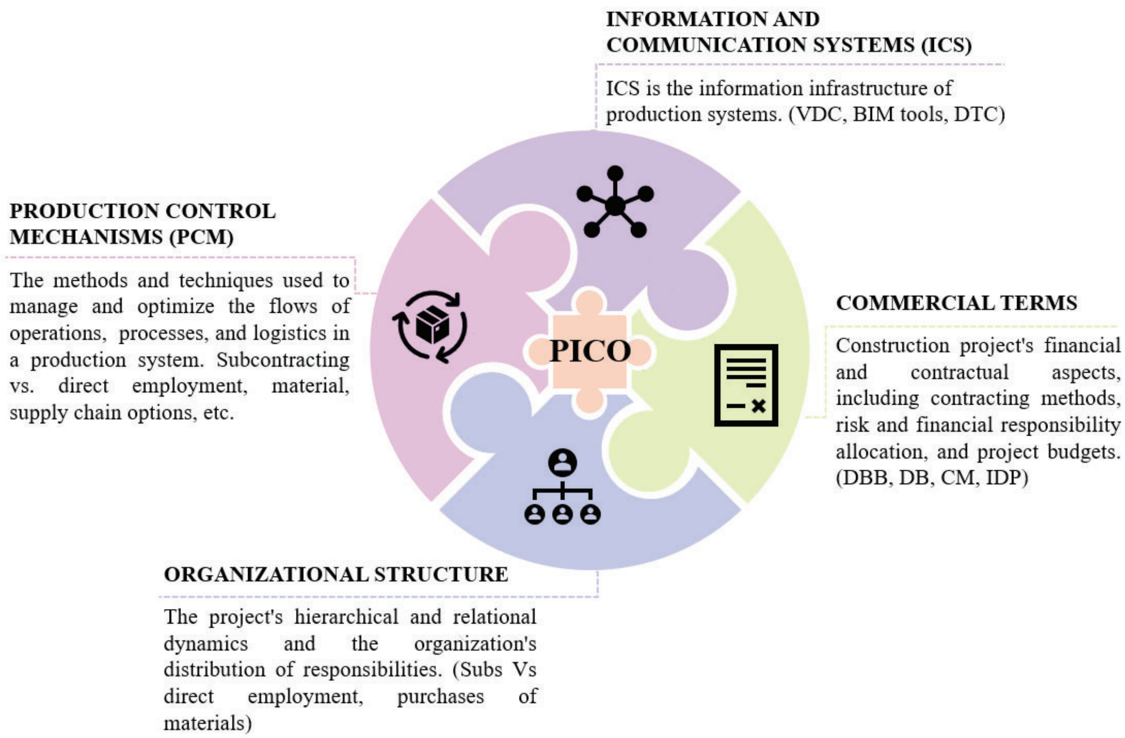

Figure 3: PICO Production System Design Framework

P - PRODUCTION CONTROL MECHANISMS (PCM)

PCM refers to the methods and techniques used to manage and optimize the flows of *operations*, *processes,* and *logistics* in a production system. PCM encompasses the 'operating system' concept defined by Mossman et al. (2010). . Among operating system tools, there are the Critical Path Method (CPM), Location-based Management Systems (LBMS), Last Planner System (LPS), Virtual Design and Construction (VDC), pull methods, Takt scheduling, and combinations of them (Kenley and Seppänen 2009; Scala et al. 2022).

Operations flow refers to the flow of production resources, such as labor and equipment, flowing through time and space (Shingo 1989 p.3).

Process flow refers to products within a building, such as apartments, classrooms, or hotel rooms, or road sections, such as bridges, lanes, or ramps. These serve as the units of production in construction and can be considered analogous to the individual products that are defined in Shingo's process-oriented definition. The policy driving process flow should seek continuous flow for those products, with zero waiting times of the products between activities, to optimize throughput, reduce cycle time and minimize Work-in-Progress (WIP) (Ballard 2001; Sacks 2016). This aspect is often neglected in traditional construction systems. Note that the units of production (products) are not the same as the locations in a location-based planning system (Kenley and Seppänen 2009), although in some cases, they may overlap.

Logistics flow refers to the movement of consumable resources, such as consumable product information (e.g., shop drawings) and raw materials, through time and space. The nature of construction sites necessitates distinguishing logistics as a flow in its own right. Good logistics flow implies managing the movement of materials so that suitable materials are delivered to the correct location at the right time in the appropriate quantity. Logistics necessitates a distinct operational approach and may involve prefabrication, pre-assembly, or fabrication on-site.

I - Information and Communication Systems (ICS)

ICS is the information infrastructure of production systems. Whereas all construction companies use basic digital tools – databases and design and detailing software, scheduling and accounting systems, and so on – many apply more sophisticated production systems, often with VDC, cloud-based information control, and site monitoring technologies. Project management tools like VICO, VisiLean, and SiteDrive are applications of these concepts used to accomplish production system goals. When designing a new production system, appropriate and effective integration of ICS is essential. Advanced ICS are indispensable for developing future production systems such as Digital Twin Construction (DTC) (Sacks et al. 2020).

C - Commercial Terms

Commercial terms refer to a construction project's financial and contractual aspects, including contracting methods, risk and financial responsibility allocation, and project budgets. The most common commercial terms in the construction industry include traditional methods such as Design-Bid-Build (DBB), Design-Build (DB), and Construction Management at Risk (CM), which differ primarily in terms of the level of risk and financial responsibility assumed by each party. Choosing the appropriate commercial terms is central to enabling the desired production system and depends on factors such as a project's size and complexity, the available resources, and the specific design and execution requirements. The commercial terms between the general contractor and trade crews who perform work, including employment conditions and compensation, as well as the purchasing and procurement of materials and assignment of risk, are pivotal in the design of the production system. They significantly impact a system's overall efficiency and effectiveness and should be carefully considered, crafted, negotiated, and agreed upon.

O - Organizational structure

The organizational structure pertains to the project's hierarchical and relational dynamics and the organization's distribution of responsibilities. For instance, the General Contractor (GC) may employ the project manager, foremen, subcontractors, or workers directly or as independent subcontractors, while the logistics and material supply management may be delegated to the GC or subcontractors. The organizational structure serves to clarify the roles and responsibilities of everyone involved in the project.

Overview

Table 1 provides a partial view of the PICO framework breakdown of its aspects and their parameters (the complete framework is available online - (Sharoni et al. 2023)The framework supports comprehensive planning for, and examination of, any project's production system components and interdependencies. The first two columns in Table 1 display the system aspects and their parameters. The third column provides the parameter values for a case study, which will be detailed in the next section.

Every decision made during the design of a new production system must consider the interdependence of its components and the tools available for its development. For instance, when setting a contract with subcontractors, the parameters must include factors such as the expected work rate, responsibility for delivery of materials to the site, procurement of materials, work performed on and off-site, budget, schedules, methods of communication, and human resources management. The contract should also address the type of payment, payments for changes during work, etc.

Table 1: Applying part of the PICO framework to a case study project. The complete framework is available online (Sharoni et al. 2023)

Aspects	**Parameters**	**Case Study Example: Weekly Takt Residential Project**
	P - Production Control Mechanisms (PCM)	
Work Packaging	Location Decomposition	Floor and building
	Work Breakdown Structure	Trade specialization
	Product Decomposition	Floor and building
	Scheduling Buffer Policy	One hour
Production planning and control methods	Look ahead planning/ constraint filtering	CPM; Last planner system - workable backlog
	Short-term work planning	CPM; Last planner system - WWP, PPC
Product changes	Coordinating	Daily meetings, WhatsApp, and E-mails
	Documenting	Self-report to a digital platform (Sitedrive)
	I – Information and Communication Systems	
Operations flow information	Trades (Workers) production rate	Experienced based trade type production rate
Process flow information (Product)	Product fabrication information LOD requirements	Medium (LOD 300)
	Product detailing process	Subcontractors provide shop drawings for review
Logistics flow information	Materials location monitoring frequency	Weekly
	Control Technologies	Digital self reporting
Platforms/ Software	Production status dashboard system	SiteDrive
	Schedule	Word, Excel, Miro, Sitedrive
	Procurement	BIM models, e-mail, Zeroni, WhatsApp
	C – Commercial Terms	
Contract	Type	DBB
	Intervening Phase	Final design
Control and flexibility	Design Control	Limited
	Flexibility for changes	Minor changes
	O – Organisational Structure	
Hierarchy	Departments/Groups/Crews	Developer, Clients (apartment purchases), Design, IT, Accounting, HR, Procurement (includes safety and quality), logistics, and suppliers.
Functional role parameters	Deliverables	Developers, Designers, Accounting, Procurement, business unit managers, site managers, foremen, subcontractors, trades, team leaders, workers, and suppliers.

CASE STUDY: TAKT SYSTEM FOR A RESIDENTIAL PROJECT

This section examines the application of the PICO framework to a case study project of a residential building project in Finland that implemented a weekly takt time approach during the interior phase. The construction company responsible for the project, FIRA Oy, reported a 20% reduction in project duration thanks to use of the takt method. However, it was noted that there were still opportunities for further improvement. Why did the production system fail to achieve the throughput aims of its designers? The PICO framework enabled rigorous analysis of the weaknesses of this case study system, as detailed below. The parameter values for the case study project are available online (Sharoni et al. 2023).

PRODUCTION CONTROL MECHANISMS

FIRA Oy utilizes a variety of control mechanisms in its production systems, including Location-based Planning and Control, Last Planner System (LPS), and takt scheduling. When implementing takt production, FIRA employs lean principles that have been partially adapted to suit the company's nature, prevailing market regulations, and cultural factors.

Operation: Trades and constraints between them are identified and implemented in a master schedule that maintains a weekly takt. While the schedule aims to present the workflow, not all trades and tasks are planned nor appear, causing a lack of documentation and an inability to monitor essential work. The takt schedule shows dominant trades but not prerequisite tasks performed by other small trades and subs, such as measurement and marking, drilling openings, sealing of openings, etc. Moreover, installing windows takes one working day per floor; yet the planned takt schedule allows the trade a week. Thus, there is work waiting for workers most of the week. Even if the trade is requested to arrive on a particular day, the trade arrives during the week subject to prioritization of other commitments. The rest of the week is dedicated to prerequisite work that was not on the schedule. The prerequisite task implementation depends on the site team's knowledge, experience, and vigilance. The extension of buffers allowed the site crew to prepare and complete the prerequisite tasks, maintaining the planned operation flow, increasing flexibility, and exhibiting a higher tolerance for errors and coordination problems. The example points out the lack of (1) detailed operation design, (2) incentive for subcontractors to arrive on time when they are aware of the project's flexibility, (3) and lack of preserving professional organizational information. All three hinder reducing the takt and will find an answer in the other PICO domains.

Process: The chosen production unit for the case study building is a floor that aligns with the location breakdown structure (LBS). The production process aims to establish a manufacturing methodology with minimal variation between floors and a work breakdown structure (WBS) comprising 300 tasks. Reducing the production unit to a room would significantly increase the number of tasks involved in planning, operating, and monitoring, as arranging different trades in the same apartment would present safety and logistics operations challenges. Manual planning of 300 tasks is already a human challenge, and extending this to over 10,000 tasks in a full-scale project would be infeasible without an automated tool.

Logistics: The procurement department, site team, and subcontractors retained responsibility for purchasing materials. However, the material ordered by the procurement department was delivered to the site by a logistics company in pre-packaged kits aligned with the LBS. This allowed for efficient delivery control as the kits were delivered directly to the operation location, reducing handling and obviating the need for storage areas. Efficient logistics support is crucial for successful takt production but requires significant resource investment. The benefits include lower transportation costs, reduced waste, and high team satisfaction. However, advanced material information is necessary for successful implementation, and last-minute orders cannot be accommodated.

INFORMATION AND COMMUNICATION SYSTEMS

The production system's schedule was created using Tocoman (https://www.tocoman.fi/) software, detailed in Word and Excel, planned on a Miro board, and then manually transferred to the SiteDrive platform. Foremen then further detailed the schedule on Excel and SiteDrive. The project design models were compiled with BIM software, and the on-site communication used 2D drawings that were updated whenever significant changes were made. Small changes or clarifications regarding details were done through direct communication and were not continuously updated in the model. The project manager was required to use multiple platforms for functions like financial planning, logistics, coordination with designers, quality and safety control, procurement, and more. Even in the best-case scenario, these platforms are only marginally interoperable. This lack of integration leads to prolonged planning, increased risk of human error, and low-resolution work, ultimately transferring responsibility to the next person in the production chain. Efficient information and communication systems have been recognized as crucial in reducing and accelerating takt production. To effectively implement shorter takt, less than a day, it is essential to have access to detailed design information and a seamless connection between procurement and material location systems. In addition, real-time progress updates, supply chain information, and the ability to quickly adapt to unexpected events are crucial in achieving success.

COMMERCIAL TERMS

The company's commercial terms with the owner are those of a DBB contract. The fixed design limits the company's ability to adapt to its production capabilities and planning priorities. Labour (subcontracted crews) are compensated using a piecework product-based system. However, in the event of any delays caused by the GC, additional payment in the form of hourly compensation may be provided to the subcontractors. The company employs specialized trade labor crews with a specific scope of professional responsibility. While prefabrication is challenging for interior construction phases, the bathrooms of all apartments (excluding those with saunas) were prefabricated in a factory, complete with all finishes, sanitary equipment, tiles, showers, and mechanical systems, ready for delivery and installation. The company works with the subcontractors using an open book method and invests in higher wages. However, the company needs to examine the correct contract method between the GC and the subcontractors, both in the scope of work type (multitasking, cleaning) and the payment method, to balance buffers implementation and payment for empty work slots.

ORGANIZATIONAL STRUCTURE

The project's organizational structure is an intricate network of connections and interactions between various stakeholders. The owner is responsible for hiring the design team and the GC. The GC communicates with subcontractors through its procurement department and its site team, which oversees the site operations. The GC also operates a logistics centre, where materials are packaged and delivered directly to the operation location to ensure efficient delivery control. The subcontractors provide specialized trade crews with a leader for each trade. Although the traditional three-party structure of owner, GC, and design team still holds, the complexity of the GC's production system expanded the project's organizational structure. Like many other companies, Fira experiences disconnection between headquarters and the site team. The soft element of an organizational structure is challenging to research and measure, connecting people and processes. However, the research indicates that the headquarters' process to implement new work methods and technology, such as takt, does not align with the understanding and needs of the site team. Additionally, duplication of purchasing responsibilities, for example, between subcontractors and the company, and contradictions between managers and internal customers hinder the implementation of changes, efficient information flow, and improvement.

From this analysis, it becomes apparent that certain parameters contribute to the optimization of the production system, such as the implementation of large buffers due to the non-detailed planning of the schedule. Conversely, other parameters can cause delays, such as a lack of planning detail. Increasing the level of planning detail can shorten the takt, reduce buffers duration, and enhance control over the production process. However, to increase the level of process detail, several requirements must be met, including greater control over product design, increased involvement of the GC, and the collection of preliminary information on the contexts and limitations between trades. Nevertheless, increasing detail alone is not sufficient to translate it into a significant financial advantage. A control system is also required for short-term management that includes the management of tasks, manpower, and materials. The case study, together with the parameters outlined in the accompanying Excel sheet, presents a complicated and intricate production system. Nonetheless, this framework provides a crucial starting point for comprehending and mapping production systems in the construction industry.

DISCUSSION AND CONCLUSION

A comprehensive approach to production system design in construction is needed, one in which every possible modification within the system is considered part of an interconnected network. To design any new production system for construction, such as a short-term takt system, for example, it is crucial to evaluate the entire production system, including aspects such as the role of the general contractor in the early design phase, the establishment of a logistics canter, the integration of technological tools to enhance takt planning, and the formation of a new organizational structure with dedicated departments. These innovations should be adopted strategically and holistically, considering their impact on the overall production system, including the flow of resources, communication, collaboration among stakeholders, and technology integration in construction processes.

The components and parameters outlined in the PICO framework are interrelated and interdependent, and their values should be set holistically. New technologies or methods should not be implemented in isolation, but rather as parts of coherent systems. In today's fast-paced and ever-evolving construction industry, incorporating a new tool for monitoring the construction process or adopting a new approach like takt, without considering the underlying production system structure, can lead to limited or suboptimal results.

This paper emphasizes the importance of redesigning the production system structure. The literature argues that the role of human capital within the production system is the key factor in a manufacturing industry's success, perhaps even more than the production system design itself, as the company's success depends on the efforts and capabilities of its intellectual capital and its staff's ability and capacity to innovate (Fane et al. 2003). However, when internal structural conflicts impair a system and the system lacks mechanisms for control, operation, management, and forecasting, even the most talented and skilled individuals may have limited ability to succeed.

Note that, although this paper presents the framework for production system design and details the PICO domain parameters and the connections between them, due to space limitations, a comprehensive analysis of the full impact of each parameter on the others is beyond the scope of this paper.

In conclusion, the challenge of improving the construction process is significant, and many possible solutions exist. However, clearly defining and understanding the issues at hand is essential, and the goal of the PICO framework is to enable just that. This work contributes to the scholarly community by expanding the current understanding of production systems in construction and presenting a new framework for defining and implementing new production systems, such as shorter-term takt production. The clear definition of construction products as distinct from locations is a key feature of the PICO framework and should enable standardization of work. A sequel paper will present the application of the framework to compare four different production systems and the consequent derivation of a production system with a takt time of one day or less.

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