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Production Planners' Scope of Action in the Context of Digital Twin Construction

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Abstract
Production planning in construction requires numerous agents, or production planners, to make operational decisions that affect the project outcomes. Decisions are based on information collected on the job site and in the project supply chain. However, difficulties accessing real-time information, the numerous production planners involved, and limitations on the planners' degree of freedom of action can hinder decision-making. Digital Twin Construction (DTC) has emerged as a paradigm for systems that increase the situational awareness of the construction project among production planners and reduce uncertainty in the decision-making process. Under the DTC frame, this research seeks to determine the scope of action of production planners. To accomplish the research goal, semi-structured interviews and a literature review were carried out to identify production planners' degree of freedom in decision-making when faced with the need for product or process changes. First, the research identifies the operational decisions that production planners make during a construction project in response to developments (as-built, as-performed information). Second, it presents a detailed analysis of production planners' main limitations during decision-making. Finally, the freedom of action of production planners was defined according to their roles. The findings are summarized in a matrix that associates operational decisions, degree of freedom, and professional roles in the context of DTC. The study results showed that production planners' scope of action is limited by the lack of real-time information concerning the construction project status and technical and legal limitations that affect their decision-making process.

Keywords
Digital Twin Construction (DTC), Production Planning, Production Planners, Scope of action, Building construction.

1. Introduction

Project planning performs a vital role in assisting stakeholders, sponsors, teams, and project managers in coordinating work through project phases. More specifically, planning pursues to identify desired goals, reduce risk and deliver a good quality product or service to the final customer. In construction, master planning is intended to determine the project activities and their logical relationships. Together with the project scheduling techniques, these processes establish the number of work packages and when each should be done.

Overall, production planning defines construction methods to be used, workers and material assignments, and elements' assembly sequence. This process is mainly conducted by production planners (individuals or groups) who decide what physical, specific work will be done in the next short-term planning window. Despite its importance, production planning faces several obstacles, including lack of information regarding construction project status, large numbers of actors or stakeholders involved in the short-term decision-making process, and production planners' limited freedom or scope of action. Scope of action in this sense refers to the range of changes that planners might make to the production system.

With the advent of new construction monitoring technologies, the construction industry has experimented with digitalization and integration of its process at all stages of the value chain (Forcael et al., 2020). Digital Twin Construction (DTC) is a new model for managing production in construction that leverages data streaming from various site monitoring technologies and artificially intelligent functions. Specifically, DTC provides accurate project status information and proactively analyzes and optimizes ongoing design, planning, and production (Sacks et al., 2020). DTC enables production planners to know the real-time status of everything happening on-site and throughout the supply chain. For instance, the current progress and quality of the work, recent locations of workers, equipment and materials, and safety conditions can be determined and evaluated. It is envisioned that DTC-derived real-time information will allow production planners to have better situational awareness and thus make better decisions. However, the quantity and nature of the information to be contained and shared through the DTC for operational level planning should be appropriate to support the types of operational decisions that production planners are able to make. Therefore, we require in-depth understanding of how production planners' scope of action affects the operational decisions in construction projects and thus the information they need.

Thus, this study sets out to understand production planners' operational decisions and limitations during a construction project and their scope of action under the DTC framework. To accomplish the study goals, semi-structured interviews and an in-depth literature review were performed to identify production planners' degree of freedom in decision-making when faced with the need for product or process changes. The findings were validated by an expert panel composed of planners from four European and American construction companies. The study results were summarized in a matrix that associates operational decisions, degree of freedom, and professional roles in the context of DTC.

2. Literature Review

2.1 Production planning in construction

Several decisions and actions are made in the construction domain based on the construction companies' expectations and goals. These decisions and actions can be categorized into two levels. From one side, administrative decisions are intended to determine the products and market the construction company will offer or act (Simu & Lidelöw, 2019). On the other hand, operational decisions frame how operations should be conducted to support the business strategy (Lidelöw & Simu, 2015). Lean construction is a typical example of an operational strategy. Lean construction is defined as a relationship-focused production management system that aims to eliminate waste from the entire construction process and deliver greater value to clients. Lean construction encourages accomplishing six principles to achieve the project goals successfully: (1) Identify the value from the customer point of view, (2) Define the value stream, (3) Eliminate waste, (4) Work to achieve smooth flow of work processes, (5) Implement Pull Planning and Scheduling, and (6) Strive for continuous improvement (Koskela et al., 2002). This approach uses various tools such as 5S, Concurrent engineering, Six Sigma, Poka-yoke, Kaizen, Kanban, and Last Planner System (LPS) to guarantee its proper implementation. At the production planning level, the LPS plays a vital role in the short-term decision-making process. The LPS process enables those who execute the work to make detailed work plans. It requires the team to review the plan near its execution specifically for collaborative planning to remove constraints and to verify that the promises made are tied to milestones and that these commitments are firm, timely, and unambiguous (Ballard, 2000). The LPS is characterized by the involvement of production planners in the decision-making process, specifically those who are required to implement short-term strategies to correct any project deviations (Salazar et al., 2020).

Various researchers have identified production planners' main actions and decisions during the course of a construction project according to lean construction and LPS principles. Pikas et al. (2012) studied different decisions that production planners make based on their perceptions of the state of readiness or maturity of the work. These decisions can result in abandoning (or stopping) the planned work or improvisation and making-do. Later, Lidelöw & Simu (2015) explored construction companies' emergent operations strategies and contrasted these with existing research on decision categories. The authors categorized the operational decisions according to lean construction principles: standardization, capacity/organization in projects, work environment, supply chain, human resources, continuous improvements, production planning, long-term perspective, process vs. project, and performance measurement.

More recently, Simu & Lidelöw (2019) investigated how the perception of operations strategy in construction practice aligns with existing theories of operations strategy. The research result showed that there are two alternative sets of operations strategies: (1) resource efficiency and (2) flow efficiency. Furthermore, the study found that standardization, supply chain, and organization are perceived as structural decision categories, and human resources, continuous improvements, long-term perspective, process vs. project, and performance management are perceived as infrastructural decision categories in construction. The aforementioned studies focused on defining possible decisions and actions that can be made according to construction companies' strategies and the production planners' perceptions. However, none of these studies established the production planners' scope of action and the limitations associated with their implementation.

2.2 Digital twins in construction

In construction projects, many actors, including production planners, are involved in making design and planning decisions that affect project outcomes. Decisions are made whenever planners determine that the current product designs or process plans can be improved upon. This may be in response to measured deviations from the designs or plans, or they may be proactive steps that result from a review of progress and performance to date. However, difficulties accessing real-time information, the numerous production planers involved, and limitations on the planners' degree of freedom of action can hinder decision-making. Thanks to the adaptation of Industry 4.0-derived technologies, several virtual and physical technologies are applied together to overcome these limitations (Forcael et al., 2020).

The Digital Twin (DT) concept has emerged over the past decade in domains such as manufacturing, production, and operations. A DT concept is defined as generating a visual and digital version of a physical object. The system could be a physical object, a social construct, or a biological system (Rosen et al., 2015). According to authors such as Tao et al. (2019), a DT has three main aspects or elements: the physical artifact, the virtual element, and the connections to bring both together. In the construction domain, a DT is a realistic digital representation of assets, processes or systems in the built or natural environment. The definition above blueprinted the creation of the Digital Twin Construction (DTC) paradigm. DTC is a novel mode for managing production in construction that uses data from various site monitoring technologies and artificially intelligent functions to provide accurate status information, enhance production planners' situational awareness, and support them using predictive analytics (Sacks et al., 2020).

Numerous researchers have explored the application of DTs in the AEC domain. Barazzetti et al. (2015) built a procedure for developing a detailed historical building information model (HBIM) using augmented reality (AR) and virtual reality (VR) to improve user community interest in cultural tourism. Gabor et al. (2016) applicated DT for online planning and presented an architectural framework focused on the information flow inside a cyber-physical system that includes the DT in a general and expandable way. The research implemented the analysis of the information flow between components of a smart cyber-physical system to the engineering process by defining a classification of different methods of controlling system behaviour with respect to the placement of said mechanisms inside the information flow. Alonso et al. (2019) created a platform with the ultimate goal of improving and optimizing buildings' energy design, construction, performance, and management, reducing construction costs and their environmental impact while increasing overall energy performance. Later, Boje et al. (2020) studied BIM applications during the construction stage and highlighted limits and requirements, paving the way to a DTC concept. Lu et al. (2020) implemented DT applications within the context of railway station buildings using a BIM-based simulation of construction work for King's Cross station in London. The research underlined the application and transformation of a 3D model of the King's Cross station building into a 6D building information model. The 6D model included a time and cost schedule with carbon emissions calculation and renovation assumptions.

More recently, Angjeliu et al. (2020) developed a method for creating an accurate digital model that combines the experimental physical reality and using it to study the structural response of the system, its preventive maintenance, and strengthening operations. More specifically, the research addressed the methodological development of structural simulation, analysis, and control models for historical buildings through the DT concept. Lu et al. (2020) performed a semi-automatic approach that establishes a systematic, accurate, and convenient DT system, integrating images and CAD drawings. Finally, Pan and Zhang (2021) developed a data-driven digital twin framework that integrates BIM, IoT, and data mining for advanced project management. The proposed solution was intended to facilitate data communication and exploration to better understand, predict, and optimize physical construction operations.

3. Research Methodology

This study aimed to determine production planners' scope of action in the context of DTC. A four-step process was implemented:

(1) Identification of the research problem and knowledge gap
(2) Develop and validate the data collection instrument
(3) Conduct the field study
(4) Systematize, analyze and validate the field study and literature review results

The following sections further discuss the four steps of the study.

3.1 Identification of the research problem and knowledge gap

During this step, an in-depth literature review related to production planning in construction, its challenges, methods and techniques, and production planning in the context of DTC was realized. Scientific articles and conference proceedings based on Web of Science and Scopus search engines were collected from the last 20 years, along with technical reports, books, and manuals on the indicated topics using the following keywords: production planning, production planning in construction, DTC, production planners' scope of action and production planners' degree of freedom. The results were summarized in the introduction and background sections.

3.2 Develop and validate the data collection instrument

A semi-structured interview was selected as the instrument for the data collection process. The interview template contained ten questions that aim to identify production planners' scope of action in decision-making when faced with the need for product or process changes. Aspects such as production planners' main decisions or actions performed to accomplish the project goals, their roles, limitations faced during the decision-making process, and the information required to take these decisions were covered in the interviews. The instrument was validated and adjusted through an expert panel, which verified its consistency and content. Table 1 presents the content and context of the instrument.

Table 3. Semi-structured interview questions.

N	Semi-structured interview questions	Context
Q1	Describe the main decisions or actions you perform to accomplish the construction project goals	Decision-making
Q2	Describe a situation or case in a construction project that required important decisions to be made to successfully achieve the project objectives.	Case study description
Q3	What decisions were made, and what changed in the production system? For example, did they add, reduce or remove resources (workers, subcontractors, equipment, materials); did they change the design in some way? Did they change something in the schedule or in the construction methods?	Decision-making
Q4	At which stage of the construction project were these decisions and changes implemented? What was the timeframe for their execution?	Case study background
Q5	Who were the main people responsible for making these decisions (owner, contractor, subcontractor, construction manager, project manager, other)?	Decision makers

Q6	Did you require authorization from other project stakeholders to take these decisions? Please explain what type of authorization you required	Authorization
Q7	Describe what types of information you needed to take the proposed decisions (plans, schedule, resources productivity rates, 3D model, budget, others).	Information requirement
Q8	Describe what project documents were modified or updated after the decision-making process.	Documents modified
Q9	Describe any limitations or constraints you faced during the decision-making process and how you dealt with them.	Decision-making limitations
Q10	Tell us about the KPIs you used to measure the feasibility of the decisions that were made and how often they were measured.	Decisions follow-up

3.2 Conduct the field study

In total,18 interviews (one-hour duration) were performed to gather information directly from production planners working in the AEC domain. Semi-structured interviews were implemented with various production planners, including site managers, project managers, foremen, and supervisors from Finland, Spain, Colombia, and Panama. It is important to mention that most of the interviewees had no prior knowledge of Lean Construction. This aspect mainly influenced the type of decisions or actions to achieve the project objectives that they proposed during the interviews. Table 2 presents the interviewees' countries of origin, their professional roles and the number of interviewees in each role.

Table 4. Number of interviewees by role and country of origin.

Interviewees' role / Country of origin	Foreman	Superintendent	Supervisor	Site manager	Project manager
Colombia	1	1		2	
Finland	1			3	
Panama	1		3	1	
Spain			1	3	1
Total	3	1	4	9	1

3.3 Systematize, analyze and validate the field study and literature review results

A qualitative approach was selected to analyze the field study results. First, the semi-structured interview results were consolidated in an Excel sheet for further analysis. Aspects such as type of project, interviewee role, location of the work (interior or exterior), nature of the problems they faced and their categories were helpful for structuring and examining the data. Second, the operational decisions made by the production planners during their construction projects were meticulously analyzed. Third, limitations that production planners faced during the decision-making process were stated. Finally, production planners' scope of action was derived and classified according to their roles and the operational decision types. The field study results were complemented with the literature review.

Production planners' degree of freedom in the process of making decisions or changes to the construction plan were categorized into three types, according to the number of actors involved and the time required to implement these decisions:

- High level decisions: require only the authorization from the site manager.
- Medium level decisions: require authorization from the site manager, project manager, and other field professionals (e.g., geotechnical engineer, structural engineer)
- Low level decisions: require authorization from several parties involved, such as the owner, project manager, site manager, and other field professionals.

An expert panel composed of planners from different European and American construction companies was formed to validate the field study and literature review results. The panel examined the tables of productions planners' operational decisions, limitations, and scope of actions according to their own previous experience on construction projects. Later, the expert panel confirmed most of the types of operational decisions stated in the tables. Finally, based on their previous experience in different construction projects, they helped refine the limitations and better define the production planners' scope of action.

4. Findings and Discussion

According to the field study results and the literature review, the main changes in the production system that production planners make during a construction project in response to developments can be categorized into two groups (see Table 3). The first group embodies decisions or actions that are made based on the conventional production model. In this model, the construction is viewed and modelled only as a series of conversion (value-adding) activities (Koskela1992). The second group embodies decisions that are made according to Lean construction principles to reduce waste and maximize customer value.

Table 5. Changes in the production system

Conventional production model	Lean construction principles
• Increase, reduce, or re-allocate resources (labor, material, and machinery) • Change the original design • Hire additional and/or replace subcontractors into the project • Reschedule some construction activities • Modify construction methods	• Standardize construction activities to reduce waste and enhance the flow of work, • Divide the jobsite into locations for measuring its performance (location-based method) • Reduce the batch size in order to decrease the work-in-progress (WIP) • Balance the capacity of the resources (labor and machinery) to minimize the non-value-added time

Production planners claimed that the resource management during the project corresponds to an operational decision that needs to be addressed during the construction phase. This decision can be oriented to adding, reducing, or re-allocating labor, material, and machinery. Another decision is derived from the need to change some aspects of the original design. This decision might involve changes in the production system and project supply chain. Comparable to the resource management decision, incorporating new subcontractors into the project could lead to changes in the production planning process, and more particularly, changes associated with the resource allocations and project duration. Rescheduling or standardizing construction activities also induces changes in the production planning process. According to the study results, this decision is mainly implemented to optimize the production flow and reduce the non-value-added time. Reducing the batch size or balancing the resource capacity are changes intended to minimize the work-in-progress and enhance the construction flow. Finally, modifying construction methods is a reiterative decision during the construction phase. It involves a change in the product and process that implies selecting the most suitable construction methods and then adjusting project resources and restructuring the project schedule.

Concerning the production planners' degree of freedom, planners involved in structural and interior work required diverse authorization levels to make decisions that may affect the project cost and duration. More specifically, decisions requiring design changes demanded a higher level of approval when compared to those that required changes in the construction method and resource modifications. For instance, modifications in the original design led to requesting the owner's approval, hindering the production planners' scope of action. On the other hand, changes in construction methods or rescheduling construction activities needed consent from site managers and other field professionals. Decisions of the latter type required less time for their authorization.

The primary limitations that affected production planners' decision-making were:

(1) lack of information concerning the current status of both interior and structural work.
(2) absence of real-time information about subcontractors' states (productivity rates, number of workers by crew and subcontractor, workers' locations, and subcontractor schedules),
(3) excessive number of people participating in the decision-making process (long chains of command),
(4) legal limitations with regards to the scope of the subcontractors' assignments, and
(5) technical limitations that hindered the implementation of the proposed solution (sch as materials specifications and preliminaries studies).

The abovementioned limitations indicate that the insufficiency of real-time information with respect to the construction project status and resources' performance highly affects production planners' decision-making process. Indeed, production planners stated that the lack of information related to resources' productivity rates, construction site's current progress, and resource locations affected their response to any change in the production system. On the other hand, technical and legal limitations also influenced the production planners' scope of action. These limitations primarily influenced the project time and resources required to implement the proposed changes.

Regarding the information requirements for implementing the proposed changes, plans and schedules were the most frequent data sources employed, especially in exterior work. In the case of interior work, resources' productivity rates were repeatedly used together with schedules. For instance, productivity rates were mainly used for assigning work crews to certain activities depending on their skills. Production planners also relied heavily upon key performance indicators (KPIs) which represented the project cost and duration. The majority of the proposed changes were assessed by comparing the actual costs and durations against the planned ones. In most cases, production planners could not determine the root causes of delays and cost overruns for each proposed change in the production system. Nevertheless, some production planners, especially those associated with structural work, implemented KPIs related to resource productivity, allowing their optimization and continuous improvement. For interior work, various production planners computed the number of defects observed during the finishing work. More precisely, they compared the number of defects identified and fixed by each crew to determine non-conformities per trade crew.

In general terms, the production planners' scope of action was mainly influenced by the availability of real-time information, the predicted impact of the decision on the project cost and duration, and the level of authorization required for implementing the changes. In most cases, site managers were responsible for making decisions during the course of the project. They primarily participated in decisions associated with operational changes that did not require design modifications, such as incorporating, reducing, or re-allocating resources (labor, material, and machinery), rescheduling construction activities, and incorporating new subcontractors. For decisions that required changes to the construction methods, the site manager needed the project manager and other field professionals' consent. For design changes, more stakeholders participated during the decision-making process. Depending on the project cost and duration impact, the owner's representative, external stakeholders (community or public institutions), and other field professionals (e.g., geotechnical engineer, structural engineer, and electromechanical engineer) participated in the design approval process.

The research findings might leverage the use of DTC-derived project status information by defining the production planners' scope of action. More specifically, DTC streams real-time information from the construction project that might be useful for production planners to make short and medium-term operational decisions. However, the literature has not yet defined the primary user of this information, what changes are possible in the production system, and what information is required to implement the actions. To depict these requirements, the following matrix (Table 4) associates operational decisions, production planners' roles, and their scope of action with the information requirements to make short and medium-term operational decisions. In the first column, the operational decisions defined through the field studies are stated. For each operational decision, actors involved during the decision-making process are established together with their degree of freedom. Then, KPIs implemented to assess the proposed solution are defined and the information requirements are associated with each operational decision.

5. Conclusions and Further Research

This study aimed to determine production planners' scope of action in the context of DTC. First a literature review and eighteen semi-structured interviews were carried out with the aim of understanding the operational decisions that production planners make during the course of construction projects. Second, an expert validated the tables of productions planners' operational decisions, limitations, and scope of actions according to their own previous experience on construction projects. Finally, the findings were condensed in a matrix that associates operational decisions, degree of freedom, and professional roles in the context of DTC.

The result showed that production planners' decisions and actions to accomplish the project goals could be categorized into two groups: decisions implemented according to the traditional transformation model in construction and decisions made according to lean construction principles. Both types of decisions are limited by the lack of real-time information concerning the construction project status and technical and legal limitations that influence the production planners' scope of action. In most cases, production planners used KPIs to measure the proposed actions by comparing the actual costs and durations against the planned ones. However, this is seen as insufficient, especially for Lean construction-derived decisions. Finally, the information requirements change due to the decision type and the number of stakeholders involved. For example, for design changes, a large amount of information is required to justify the feasibility of the change. Instead, to balance resource capacity and minimize WIP, only the project schedule was required.

This research has some limitations that need to be stated explicitly. First, the number of semi-structured interviews was limited to only eighteen. Further studies need to be conducted with more production planners of different countries and companies to contrast the result obtained. Finally, the production planners' scope of action matrix did not incorporate a time scale that allows decision-makers to understand the time required for implementing the proposed solutions. Future research needs to be carried out for incorporating temporal relevance into the constructed matrix to associate timescale with the identified actions.

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Table 6. Production planners' scope of action matrix

		Decision makers								KPIs used									Information requirements					
		Foreman	**Superintendent**	**Site manager**	**Project manager**	**Other filed professionals**	**Owner representative**	**Owner**	**Others stakeholders**	**Activity total cost**	**Activity total duration**	**Labor productivity rate**	**Machinery productivity rate**	**Labor utilization rate (per crew)**	**Machinery utilization rate**	**Non-value-added time**	**Work-in progress (WIP)**	**Cycle time**	**Plans**	**Budget**	**Schedule**	**Technical specifications**	**Contract**	**Production planners' degree of freedom**
1	Increase, reduce, or re-allocate resources (labor, material, and machinery)	X	X	X						✓	✓	✓	✓	✓	✓					☑	☑			High
2	Change the original design			X	X	X	X		X	✓	✓	✓	✓						☑	☑	☑		☑	Low
3	Hire additional and/or replace subcontractors into the project			X	X					✓	✓	✓	✓							☑	☑			Medium
4	Reschedule some construction activities		X	X						✓	✓	✓	✓	✓	✓						☑			High
5	Modify construction methods			X	X	X				✓	✓	✓	✓							☑	☑	☑		Medium
6	Standardize the construction activities to reduce waste and enhance the flow of activities.			X						✓	✓	✓	✓	✓	✓	✓	✓	✓		☑	☑	☑		High
7	Divide the jobsite into locations for measuring its performance (location-based method)			X	X					✓	✓	✓	✓	✓	✓	✓	✓	✓	☑		☑			High
8	Reduce the batch size in order to decrease the work-in-progress (WIP)	X		X						✓	✓						✓	✓			☑			High
9	Balance the capacity of the resources (labor and machinery) to minimize the non-value added time	X		X								✓	✓	✓	✓	✓		✓			☑			High

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