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Combining decentralized decision-making and takt production in construction planning and control to increase production flow

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Takt production and decentralized decision-making have been recent areas of interest in (lean) construction management research. Both have the potential to improve flow and contribute to increased production performance. Despite the interest, the efforts toward decentralization have not effectively considered the first-line workers; simultaneously, takt production studies suggest that neglection of workers' involvement has led to implementation challenges and hampered flow. Thus, combining decentralized decision-making (including the involvement of the first-line workers) and takt production could have the potential for further improving production flow and performance. By utilizing design science research, this explorative single-case study aimed to evaluate the effect of decentralized decision-making and takt production to production flow through formulating, implementing, and validating a decentralized takt production framework. The primary data were collected from three production planning sessions and 17 semi-structured interviews, supported by site observations, resource tracking data, schedule data, cost data, and production progress reports. The framework formulation and validation were also supported by six expert workshops. The findings indicate that decentralization can be combined with takt production, aiding production flow. Good operations flow was especially aided by decentralized decision-making. These positive effects were supported by observations of improved utilization of site teams' knowledge in planning, better commitment, communication, team-building process, and positive competition between teams. In addition, 23% duration savings were achieved in the production phase in which the framework was implemented. Also, stable resource utilization of trades was achieved. The decentralized decision-making practices were successfully implemented in the planning phase; however, the elements of decentralization were not adequately utilized in the control phase, resulting in the intended benefits not being obtained to their full potential magnitude. An extensive effort over single projects and organizations would be needed to gain all the intended benefits, while the competence to successfully operate with (decentralized) takt production increases with experience. The study makes scientific and managerial contributions to improving construction production planning and control practices and flow by exploring the combination of decentralized decision-making and takt production and by considering site teams and first-line workers' viewpoints, which have been scarce in previous research.

KEYWORDS

construction management, production planning and control, decentralization, takt production, production flow, design science research, case study

Introduction

Takt production has been increasingly studied in construction management research over the last decade. Takt production is a location-based production planning and control[1] (PP&C) method, aiming to increase production flow by considering the effective utilization of space in construction sites and adopting insights from the most prominent lean construction and lean manufacturing best practices (e.g., Frandson et al., 2013). In lean, the focus is on performing actions just-in-time (JIT), advocating built-in quality, building standardized and low-variability processes, and continuous improvement with the high inclusion of people (Liker, 2005). Following these practices, takt production operates by planning tasks and resources to proceed at a consistent beat, "takt," that matches the client's demand (takt planning), steering the production as deviations or problems arise to maintain the beat (takt control) (Dlouhy et al., 2016), and continuously improving the system (Lehtovaara et al., 2021). Takt production is a potential way to increase production flow, efficiency, and production performance. The documented benefits include significant production duration reductions (Frandson et al., 2013; Binninger et al., 2018), improved quality, safety (Heinonen and Seppänen, 2016), and worker productivity (Kujansuu et al., 2020), with increased transparency of communication and production control effectiveness (Linnik et al., 2013). These benefits have been documented even when implementing takt production for the first time, with no prior experience utilizing the method (e.g., Lehtovaara et al., 2019).

Another research stream that has recently shown potential in improving construction production performance is the decentralization[2] of decision-making in PP&C processes. In construction, the mainstream PP&C methods (such as the critical path method, CPM; Plotnick and O'Brien, 2009) have assumed that production can be successfully managed through central and hierarchical decision-making. However, the truthfulness of this assumption has long been questioned (e.g., Johnston and Brennan, 1996). Decentralized, autonomous decision-making has gained broad interest in the project, organization, and production management domains, demonstrating benefits such as increased efficiency, creativity, and well-being of workers in, for example, the military (McChrystal et al., 2015), manufacturing (Liker, 2005), and healthcare (Laloux, 2014). In construction, decentralization of PP&C has been promoted, particularly in the context of lean construction, through methods such as the Last Planner® system (LPS, Ballard, 2000), yielding promising results for increasing production performance (Castillo et al., 2018). LPS has also been utilized in parallel with other PP&C methods to improve collaboration. Indeed, the combination of CPM and LPS (Huber and Reiser, 2003), the location-based management system (LBMS) and LPS (Seppänen et al., 2010), and takt production and LPS (Frandson et al., 2014) have all shown promising results in bringing synergies to each other while emphasizing decentralization.

Despite the interest in decentralization in construction, the efforts to decentralize PP&C have not effectively considered the first-line workers but mainly focused on collaboration between managers and crew leaders (Lehtovaara et al., 2022). This is surprising as considering workers' input when forming a plan, involving them in controlling the production, and nurturing continuous improvement through their ideas is at the heart of lean in manufacturing (e.g., Liker, 2005). Several takt production implementation initiatives suggest that neglecting workers' involvement has led to implementation challenges, hampering flow (e.g., Vatne and Drevland, 2016). Decentralized decision-making could be especially suitable in takt production, as takt planning requires an early, detailed understanding of the production process that site crews and especially workers possess. Moreover, takt control calls for immersive involvement of all site personnel to act on the emerging issues on time and learn from them while keeping production on track (Lehtovaara et al., 2021). However, combining takt production with decentralized decision-making involving first-line workers has not been previously studied.

Therefore, it could be argued that if the possibilities of decentralization (including the involvement of the first-line workers) were considered when implementing takt

1 Being a vital part of production management, PP&C processes determine what and when to produce and how to control the production in a way that achieves the initiated plan (Vollmann et al., 1997). While planning gives a structure for the production's progress, control is needed to keep the production on track in the event of something unforeseen happening.

2 Decentralization denotes a process by which the decision-making responsibility is shared from an authority to lower levels of the hierarchy (Mintzberg, 1983). In construction PP&C, decentralization could be realized as dispersing the planning and control authority from the project and site managers to site teams, comprising trade crew leaders and workers.

production, the potential of takt production in aiding flow could be further increased. An interesting research avenue emerges from these premises, allowing us to formulate the research question (RQ) for this study: *how could combining takt production with decentralized decision-making affect construction PP&C practices and production flow?* To answer the RQ, we employ a design science research (DSR) approach to formulate, implement, and validate a PP&C framework that allows evaluating the effect of decentralized takt production on production flow. The framework is implemented in an industrial construction project in central Finland, where an existing manufacturing plant was extended with a new warehouse building, consisting of ~10,000 m^2 of space. The implementation targets the interior phase of the project, especially the mechanical, electrical, and plumbing (MEP) work. The study is limited to the interior phase of a building construction project to sharpen its focus. This is an explorative study that, by utilizing qualitative and quantitative evidence, aims to provide insights into how decentralized takt production could affect construction production flow and production management practices.

Theoretical background

Construction production flow and takt production

Flow plays a vital role in achieving robust performance in any production process. Production flow can be understood as a transformation of materials into products as they move through a value stream, where a series of value- (and non-value-) adding actions are performed (Rother et al., 2003). Good flow occurs when the transformation across the value stream occurs swiftly and evenly (Schmenner and Swink, 1998), with few non-value-adding actions (Womack and Jones, 2003). Specifically, production flow can be inspected from two different but intertwined perspectives: process and operations flows (Shingo and Dillon, 1989). In construction production, process flow denotes the flow of sequenced activities performed in a single location (e.g., an apartment), while operations flow means the flow of a single activity performed by a trade crew in different locations (Sacks, 2016). Sacks (2016) distinguishes the elements of good flow in a construction project's production: the first eight elements (P1–P8) are related to process flow, and the latter two (O1–O2) refer to operations flow:

- P1: (process flow condition 1): The variation of takt times[3] across locations is minimized.
- P2: The batch size (the number of locations occupied by a trade crew) is minimized.
- P3: The sum of time buffers between activities is minimized.
- P4: The number of unnecessary activities is minimized.
- P5: The amount of re-entrant[4]f flow is minimized.
- P6: The amount of rework is minimized.
- P7: The amount of making-do is minimized.
- P8: The amount of work in progress (WIP) is minimized.
- O1: (operations flow condition 1): The variation in each trade crew's takt time is minimized.
- O2: Set-up, inspection, and non-value-adding times are minimized.

Effective PP&C methods play a fundamental role in achieving good flow (e.g., Koskela, 1992; Liker, 2005). In construction, various methods have been implemented to achieve this objective; in particular, the so-called location-based planning and control methods (e.g., line of balance; Pe'er, 1974; and LBMS) have been implemented and proven to contribute positively to flow (e.g., Olivieri et al., 2018), compared to widely used, activity-based methods (such as CPM), which do not effectively consider the utilization of space and mostly neglect the role of flow. Location-based planning is akin to space planning, which both consider locations as critical resources (Akinci et al., 2002). Furthermore, spatiotemporal planning methods have been developed that use algorithmic and graphical approaches to ensure smooth utilization of locations and resources; these have also been conceptually examined with takt production (Francis et al., 2019).

In contrast to other location-based methods, whose primary aim has been to enable steady operations flow, in takt production, the aim is to increase process and operations flows simultaneously, making it a prominent candidate to achieve all ten elements of good flow. In practice, the most notable difference between takt production and other location-based methods is the prioritization of standby capacity buffering over time and space buffers, supporting timely and reliable handoffs (Frandson et al., 2015) and thus the flow of processes. Indeed, takt production has been perceived as positively affecting overall production flow (e.g., Linnik et al., 2013). Dlouhy et al. (2017) also argue that takt production could provide additional synergies for industrial construction, in which interlacing construction and equipment installation phases allows faster and more reliable handovers, increased overall project flow, and reduced overall project duration. Lehtovaara et al. (2021) have observed that implementation maturity also

3 In construction, takt time refers to the required duration for completing a certain activity in a given location to match the client's needs (Dlouhy et al., 2016).

4 Re-entrant flow occurs when a trade crew needs to access a work location multiple times at different process stages (Brodetskaia et al., 2013).

affects results; in cases where takt production is implemented with no prior expertise, it has contradictory effects on operations flow (negative effects being such as increased resource fluctuation), but with increased experience, the results for both process and operations flows are primarily positive.

Takt production implementation consists of three predominant steps (adopted from Lehtovaara et al., 2021): takt planning, production ramp-up and takt control, and continuous improvement.

Takt planning

In takt planning, the aim is to create a production plan that employs balanced process and operational flows. The process begins by addressing the client's needs for production that form the basis for initiating flow (Frandson et al., 2013) and by collecting relevant production data as the basis for planning (e.g., including a list of production tasks, their sequence, estimated production rates, location-based quantities, available resources, deadlines, and other priorities). The plan is further developed by increasing the level of detail. These planning horizons are formed similar to the planning horizons of LPS (e.g., Ballard and Tommelein, 2021). The planning process consists of iterating several planning parameters: size and form of locations (takt areas) where a batch of activities are simultaneously conducted, work packages that contain the batch of activities (takt wagons), the time in which the batch of activities should be completed in a single takt area (takt time), and resourcing (Binninger et al., 2017). The plan is further balanced by integrating capacity, inventory, and time (Hopp and Spearman, 2011), and plan (Frandson et al., 2015) buffers into the plan to cope with production variability. Takt planning especially contributes positively to flow elements P1–P4 and P8 (Lehtovaara et al., 2021).

Production ramp-up and takt control

During production ramp-up, the production pace is set, and the initial emerging problems are solved. More time for work in the first takt areas can be planned to ensure a "soft" start and additional time to solve unforeseen problems during ramp-up. Takt control itself aims for timely, short-cycled, and visual production management, with an emphasis on effective quality control (Dlouhy et al., 2016). In takt control, the primary aim is to achieve stable handoffs for every wagon, where problems are immediately identified and solved before the next wagon's activities begin (Frandson et al., 2015). Takt control requires more effort at the beginning of production. Later on, it has been reported to result in increased process and operations flows, especially contributing to flow elements P5–P7 and O1–O2 (Lehtovaara et al., 2021).

Continuous improvement

Continuous improvement in and across projects is necessary to increase production flow over time and reduce the effort needed in subsequent projects' takt planning and control phases. Takt production makes emerging problems highly visible and creates an urgency to solve them. Addressing them requires an increased effort at first but offers an opportunity for effective production system improvement in the long term (Lehtovaara et al., 2021).

Decentralized planning and control

The decentralization of planning and control has produced multiple benefits in various domains and industries. These benefits include enhanced project performance; increased capability for skill development; better performance in conflict situations (Humphrey et al., 2007; Yang and Guy, 2011); and increased proactivity, commitment, creativity, motivation, and well-being of workers (Mintzberg, 1983; Richardson et al., 2002). In the construction PP&C context, the observed benefits include greater process transparency, improved plan reliability, reduced dependability on individual leaders, and reduced waste (Priven and Sacks 2015; Lehtovaara et al., 2022), with a positive contribution to project time and cost performance (Castillo et al., 2018).

Despite these benefits for projects and project personnel, decentralization has also been perceived as having disadvantages compared to centrally led management practices. Koskela et al. (2019) also argue that an appropriate combination of centralized and decentralized approaches often offers the best solution instead of opting for only one. With inappropriate balance, decentralized practices might result in inconsistent coordination and communication between teams (Stinchcombe and Heimer, 1985), hampered information flow and knowledge sharing (Mintzberg, 1983), and excessive risk-taking (Lanaj et al., 2013), especially in instances with a high degree of complexity and a large number of interdependent teams (Leavitt, 2005).

To successfully implement decentralized planning and control while avoiding possible disadvantages and considering the first-line workers, the following drivers have been suggested in previous studies:

- Ensuring early and intense involvement of site teams, officially determining their responsibilities in decision-making, and allocating adequate time and resources for individuals' decision-making and problem-solving through the production (Chinowsky et al., 2010; Saurin et al., 2013; Lehtovaara et al., 2022)
- Training teams and individuals to cope with their increased role in decision-making and supporting managers to act as facilitators rather than autocrats (Bertelsen and Koskela, 2005; Pikas et al., 2012; Saurin et al., 2013; Lehtovaara et al., 2022)
- Initiating trust and transparency between site teams and individuals through team-building and mutual access to

information flow (Howell and Ballard, 1998; Baiden et al., 2006; Chinowsky et al., 2010; Lehtovaara et al., 2022)
- Empowering site teams and individuals for autonomous decision-making in practice while building cultural change toward a broader recognition of decentralization (Saurin et al., 2013; Magpili and Pazos 2018; Pryke et al., 2018; Lehtovaara et al., 2022).

Based on the literature, it seems that takt production could be suitably combined with decentralized decision-making to achieve increased flow. The approaches have several complementary points, and the decentralization drivers could possibly be embedded in the takt production process. For example, greater process transparency and improved plan reliability are necessities for successful takt production, needed in every implementation step. Intense involvement and training of site teams would support learning the requirements of takt production, while individuals would be better committed to executing the plan. Encouragement for autonomous decision-making can also help better utilize the site teams' knowledge in the process and reduce the workload of managers, which often increases in (first) takt implementation initiatives (e.g., Lehtovaara et al., 2021). In the following sections, we examine how the combination of takt production and decentralized decision-making can be realized in practice.

Materials and methods

Research strategy

We employ DSR as a research strategy, which allows us to answer the RQ by formulating, implementing, and validating a decentralized takt production framework. In DSR, the researcher takes an active role as a problem-solver instead of a sole observer, enabling an in-depth, meaningful reflection on the observed phenomena (Holmström et al., 2009). In this study, DSR comprises four phases, guided by Kuechler and Vaishnavi's (2008) approach: 1) problem definition and presentation of relevant literature (already presented in the introduction and theoretical background sections); 2) formulation of a framework and case study preparation; 3) implementation and validation of the framework; and 4) discussion of the findings and formulation of the study conclusions.

A case study was chosen as a primary research method. A case study allows drawing conclusions from a complex issue while inspecting it in a real-life context through an element of substantial narrative (Flyvbjerg 2006). Moreover, a single-case study approach was chosen to gain focus and depth in data collection and analysis. Tellis (1997) (p. 3) points out that a single-case study is especially suitable for "revelatory cases where an observer may have access to a phenomenon that was previously inaccessible" and is thus ideal for exploring decentralized takt production. The flow of the study is presented in Figure 1 and further elaborated in the remainder of this section. The process for formulating and validating the framework through expert workshops is presented on the left side of the figure, while the case study process is presented on the right side.

Framework formulation and validation: Expert workshops

The study was conducted as part of a larger Finnish research project, in which a consortium of 21 companies and a university research group (Lavikka et al., 2020) explored the application of decentralized PP&C to construction production. To aid in formulating the framework, preparing the case study, and validating the results, six expert workshops (that were part of the research project) were held as a supporting research method. A workshop is a qualitative research method that can be used to gain feedback and insights on novel phenomena, such as process or product innovation, through interactive group sessions (Thoring et al., 2020). Facilitated workshops with domain experts are often conducted when an explorative touch and various viewpoints are needed regarding a scarcely studied topic to provide insights for evaluating initially formed ideas (Ørngreen and Levinsen, 2017).

In total, six expert workshops were conducted with representatives of general contractors, construction management consultants, design consultants, trade contractors, and software developers who were invited by the companies participating in the research project. In our study, an expert is defined as a person with domain knowledge of construction management and an interest in developing construction PP&C practices. Participation was not restricted by years of experience or employment title to allow a broader discussion with a wide range of opinions. Approximately 30 experts participated in each workshop (the number slightly varied between sessions). The same base pool of participants was maintained throughout the study to enable them to form a shared mindset and achieve a safe space to exchange insights and accumulate learning over the course of the sessions (Race et al., 1994).

The workshop structure, themes, and their relation to the case study are presented in Figure 1. The workshops were embedded in bi-monthly, half-day research workshops, which were arranged specifically to explore the application of decentralized PP&C. The authors served as facilitators, actively participating in the discussions. The session lengths were 60 min in sessions 1, 2, and 6 and 30 min in sessions 3, 4, and 5. The discussion was mainly held within the whole group but occasionally broken into smaller groups to enable each attendee's active participation (Ørngreen and Levinsen, 2017). We took notes from the discussion, and insights were also

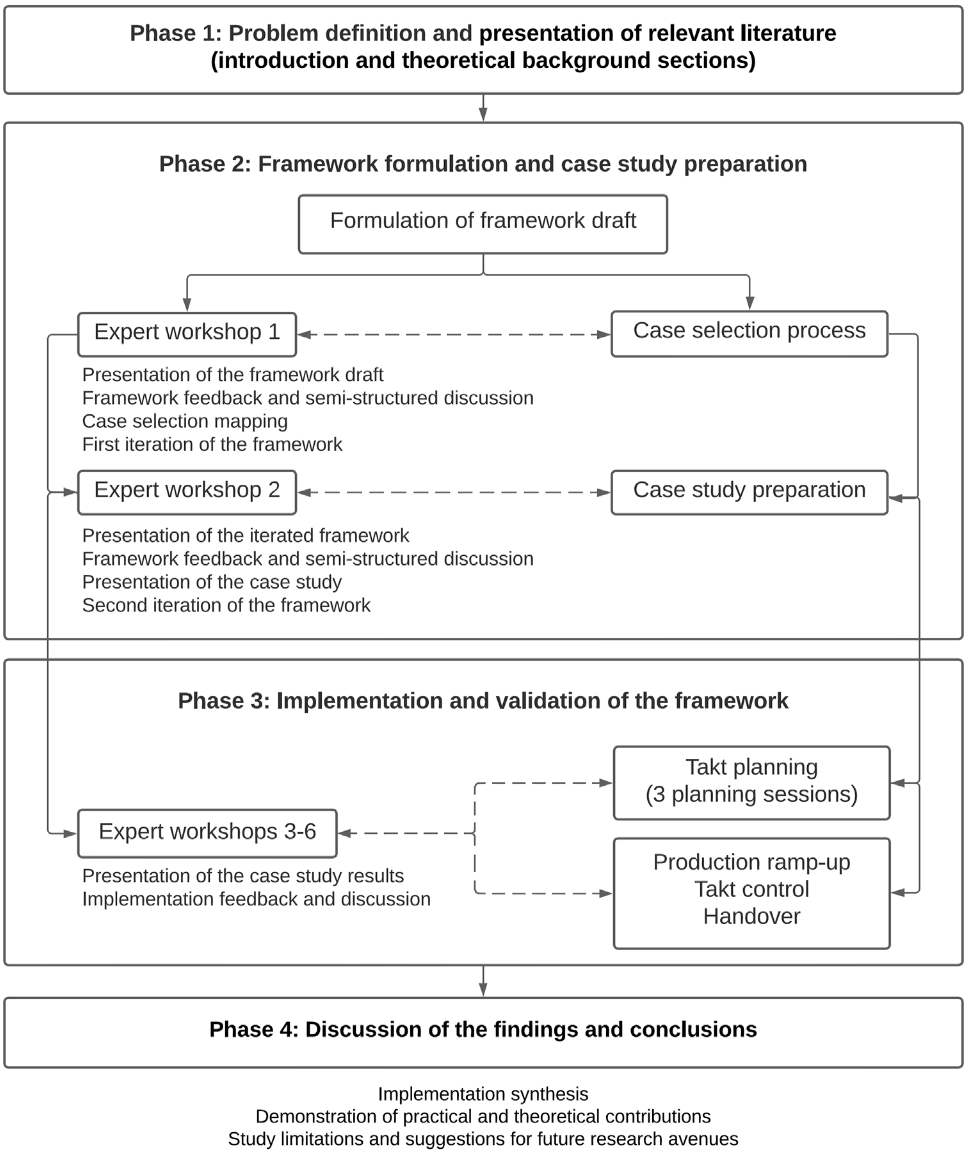

FIGURE 1
The flow of the study.

gathered using a web-based activation software in which the respondents answered the guiding questions during the session. Workshops 1 and 2 were conducted as live sessions, but due to the COVID-19 pandemic, the rest of the sessions were conducted virtually.

Case study

The possible case candidates were mapped during the first expert workshop, primarily looking to implement the framework in the represented companies' projects. The case was selected based on two criteria: willingness and ability to implement the framework; and access for data collection, including the possibility for site visits and interviews. The selected case was an industrial construction project in central Finland, where an existing manufacturing plant was extended with a new warehouse building, consisting of ~10,000 m^2 of space. The project's construction management company was eager to implement decentralized takt production to reach construction milestones, which were perceived as nearly impossible to achieve without a refined PP&C approach. The implementation targeted

TABLE 1 Summary of the case study data sources.

Data sources in the takt planning phase	3 planning workshops; researchers acted as facilitators. Takt planning data: schedules, meeting minutes, project diary, and workshop observations. 5 semi-structured interviews with crew leaders and workers *I1: Crew leader, sprinkler installation I2: Crew leader, electricity works I3: Worker, electricity works I4: Crew leader, general MEP works. I5: Worker, general MEP works*
Primary data sources in the takt control phase	5 semi-structured interviews with crew leaders and workers *I6: Worker, sprinkler installation I7: Crew leader, electricity works (same interviewee as in I2) I8: Worker, electricity works (same interviewee as in I3) I9: Crew leader, general MEP works I10: Worker, general MEP works. 7* semi-structured interviews with managers and a client representative *I11: Project manager, electricity works I12: Project manager, sprinkler installation I13: Project manager, general MEP works I14: Project manager, construction manager consultant I15: Project engineer, construction manager consultant I16: Site supervisor, construction manager consultant I17: Project manager, client*
Supporting data sources	Resource tracking data, schedule data, cost data, meeting minutes (including tracking of preconditions for/barriers to work), and a project diary written by a project manager. Observation: a site visit, and participation in two production meetings

the interior phase of the project, especially the mechanical, electrical, and plumbing (MEP) work, which were regarded as production bottlenecks. One of the authors (EL) was employed by the construction management company during the study, but did not have a role in the case project.

The sources of the collected data consisted of two primary and one supporting categories, respectively: 1) facilitation and observation of three takt planning sessions; 2) 17 semi-structured interviews with case participants; and 3) site observations, resource tracking data, schedule data, cost data, and production progress reports. The data sources are presented in Table 1. First, takt planning was conducted in three sessions in which the researchers acted as facilitators, guiding the process while training the project personnel to operate within the framework. Schedule and observation data were also collected during the takt planning phase.

Second, three rounds of 17 semi-structured interviews with a total of 15 interviewees (some of the interviewees were interviewed twice at different stages of the implementation) were conducted to obtain insights regarding the implementation. Semi-structured interviews were utilized to allow the participants to reflect on their experiences freely while guiding the conversation toward the RQ. The first and second interview rounds focused on the framework implementation from the site team's perspective, and the interviewees were trade crew leaders and workers. The third interview round focused on a managerial perspective, with the interviewees consisting of managers and a client representative. The first interview round was conducted on-site, but the second and third rounds were conducted virtually due to the COVID-19 pandemic. The interviews were recorded and transcribed, and the notes made during the interviews were also utilized in the analysis.

Third, production and observational data were collected to support the other data sources. The collected data included resource tracking data, schedule data, cost data, meeting minutes (including tracking of preconditions for/barriers to work), and a project diary written by a project manager (in which the site's progress was reflected daily from the construction manager's point of view). The data were obtained from general project documentation maintained by the construction management company. The observations were based on a site visit and participation in two production meetings. The COVID-19 pandemic restricted the possibilities for additional site visits and observation of site meetings. However, during the implementation, the authors were in close contact with the site personnel on a weekly basis, allowing data collection and observation of the site's progress remotely. In total, data collection lasted for 15 months (June 2019–August 2020).

Data analysis

The procedure for compiling and analyzing the data progressed through the development of the narrative, followed by data reduction and coding (Miles and Huberman, 1994). All the data were thematically coded and structured according to the inspected second-order (implementation steps, i.e., takt planning) and first-order themes (drivers/benefits/challenges, i.e., involvement of workers) and interpreted by looking for similarities, differences, and emerging themes among the responses and different data sources. Simultaneously, data that were not strictly related to the formulated themes were reduced to gain focus in the analysis and to reduce information that was not necessary to answer the RQ.

The workshop and the case data were partially analyzed and triangulated reciprocally during the implementation and validation phases, laying the ground for continuous discussion and feedback among the workshop experts, the case study participants, and the study authors. The main author was primarily responsible for analyzing and synthesizing the workshop and the case data, which helped align the discussion and the analysis among the authors. During analysis, illustrations and synthesis tables were also drawn from the results to guide the discussion and to provide a graphical representation of the results. Through iteration, these graphical representations formed the illustrations presented in the results section.

TABLE 2 Decentralized takt production framework.

Process step	Drivers for decentralization	Contribution to flow
1a Data collection and high-level takt planning		
Data collection: relevant production data are collected to form the basis for high-level takt planning. Data are gathered from building information models, productivity databases, and labor agreements and supported by the participants' personal experience. **High-level planning:** consists of defining goals and milestones based on the client's preferences, which allows determining initial values for the planning parameters (takt areas, takt time, takt wagons, buffers, and resourcing), further resulting in the first iteration of the production plan that sets boundaries for further, more detailed planning. It is conducted centrally by a "core" team, including, for example, the general contractors (GCs), project and site managers, the client, and possibly trade contractors' managers.	Centralized decision-making allows a meaningful overall balance between centralized and decentralized approaches and to effectively assess the overall flow and client's needs (Koskela et al., 2019, expert workshop feedback).	The focus is on initiating good overall flow, especially considering process flow conditions P1–P4 and P8 (Lehtovaara et al., 2021, expert workshop feedback).
1b Formulation of teams and decentralized takt planning		
Formulation of teams: the step begins by the core team forming wagon-based planning teams, which are based on the high-level plan and consist of trade crew leaders and workers that are part of the work activities within specific wagons. **Decentralized takt planning:** especially focuses on iterating the process within wagon teams by, for example, iterating task durations and sequence, buffers, and resourcing. The iterated decisions are reflected in the overall takt plan, while constraints and requirements for other wagons are communicated and solved in collaboration with the core team and other wagon teams. The teams should mutually agree on changes in mutual planning parameters (takt time, takt areas, wagon sequence task distribution, and buffers). The core team facilitates the process.	Ensures early, gradual, and intense involvement of teams; officially determining their responsibilities in decision-making; and allocating adequate time and resources for decision-making and problem-solving (e.g., Saurin et al., 2013, expert workshop feedback). It initiates trust and transparency amongst site teams and individuals (e.g., Chinowsky et al., 2010).	The focus is on improving operations flow (O1–O2) and ensuring that overall flow is maintained during the decentralized planning (initial discussions and expert workshop feedback).
2 Production ramp-up and takt control		
Production ramp-up: final coordination of takt control procedures is conducted to ensure a smooth start. Control mechanisms presented by Binninger et al. (2017) were adopted for takt control, which are also trained for all the participants before the production begins. **Takt control:** consists of short-cycled and visual production management through short progress meetings held every day by the core and site teams, accompanied by systematic quality control (including handoffs between every wagon where the quality defects are issued and preconditions for the next wagon are ensured). The decision-making authority to tackle more minor issues should be held within the decentralized teams, gradually involving other teams and the core team in the decision-making if necessary. The core team facilitates the process.	Empowers teams and individuals for autonomous decision-making in practice and ensures daily communication between site teams and management (e.g., Magpili and Pazos 2018, expert workshop feedback).	The focus is to especially ensure flow conditions P5–P7 and O1–O2 while maintaining good overall flow (Lehtovaara et al., 2021).

(Continued on following page)

TABLE 2 (*Continued*) Decentralized takt production framework.

Process step	Drivers for decentralization	Contribution to flow
	3 Continuous improvement and training	
Continuous improvement (that aims to tackle emerging problems immediately) and training of the participants (especially trade crew leaders and workers, but also the core team members) should be ensured during the planning and control phases, and between projects.	To cope with the increased decision-making responsibility, individuals are trained and involved through the planning and control process (e.g., Saurin et al., 2013, expert workshop feedback).	Supports maintaining overall flow (Lehtovaara et al., 2021).

Results

Framework formulation and implementation process

The decentralized takt production framework was formulated based on the theoretical background and improved with feedback obtained from expert workshops 1 and 2. Table 2 describes the framework and how decentralization and production flow are considered in specific steps. Compared with other takt production approaches, such as takt time planning (TTP) (e.g., Frandson et al., 2013) and takt planning and takt control (TPTC) (e.g., Dlouhy et al., 2016), the presented framework has similarities with both; the overall process is aligned with the general implementation steps of takt production, which both TTP and TPTC utilize (Lehtovaara et al., 2021, see theoretical background). The most notable difference is that in the framework, the process is clearly split into centralized (high-level planning) and decentralized (decentralized planning, takt control, and continuous improvement) phases; in the decentralized phase, decision-making responsibility is partially distributed to the site teams and first-line workers, while the managers act as facilitators and ensure connectivity among the teams. TPTC is primarily driven in a centralized fashion, while in TTP, trade crew leaders' input is heavily used to aid in decision-making, initiating decentralization.[5] However, in TTP, the decision-making is still not extended to the worker level. Moreover, in contrast to TTP and TPTC, the proposed framework explicitly emphasizes the drivers of effective decentralization of decision-making, for example, by considering the site teams' needs in the decision-making process and providing them with adequate resources to succeed with their increased responsibilities.

In the inspected case, high-level takt planning was conducted through two planning sessions, and personal tasks (such as acquiring information and feedback) were assigned before and between the sessions to aid the planning process. In a third planning session, the formulation of wagon-based teams (composed of crew leaders and workers) and further iteration of the plan in a decentralized manner were conducted. As a result, the takt plan was divided into eight takt areas, consisted of 11 takt wagons, and proceeded with a 1-week takt time. In addition to the plan iteration, the takt control process was prepared in the third session. Takt control was planned to be coordinated through short daily site meetings, accompanied by longer weekly meetings in which the prerequisites for the subsequent week's work would be addressed. The participants were trained in using takt control mechanisms during the third planning session, which were also visualized in the site office. Because of the tight milestone dates demanded by the client, a soft start was not implemented, but it was agreed to pay increased attention to the production ramp-up.

Implementation findings

The implementation positively impacted project schedule performance, as illustrated in Figure 2. The original interior schedule was planned for 22 weeks, but due to a 6-week delay in the procurement process, the project team was pushed to seek improvement to reach the equipment installation start date required by the client. Takt planning resulted in a schedule of 17 weeks with interlaced handovers between construction and equipment installation, meeting the client's demands. The actual length of the interior phase ended up being 20 weeks (a duration reduction of 9%), but due to successful phase interlacing, the equipment installation was allowed to start at the desired date, resulting in a duration savings of 6 weeks or 23%. A project engineer stated that this would have been "impossible to achieve without the implemented framework" (I15). The positive effects on schedule performance were especially welcomed by the client (I17). For the client, meeting the specified milestone dates and visually understanding the schedule progress were seen as the most positive results of the implementation.

Challenges, primarily induced by external factors, caused a slight increase in the interior phase's length from the planned 17 weeks. The COVID-19 pandemic began during the production, resulting in quarantines, limited personnel access to the site, and material delivery problems. Additionally, a winter storm caused damage to an external wall, which slowed the work

5 While the TTP method descriptions do not present an explicit control approach, combining TTP with LPS has been proposed to provide an integrated approach for takt control and continuous improvement (Frandson et al., 2014).

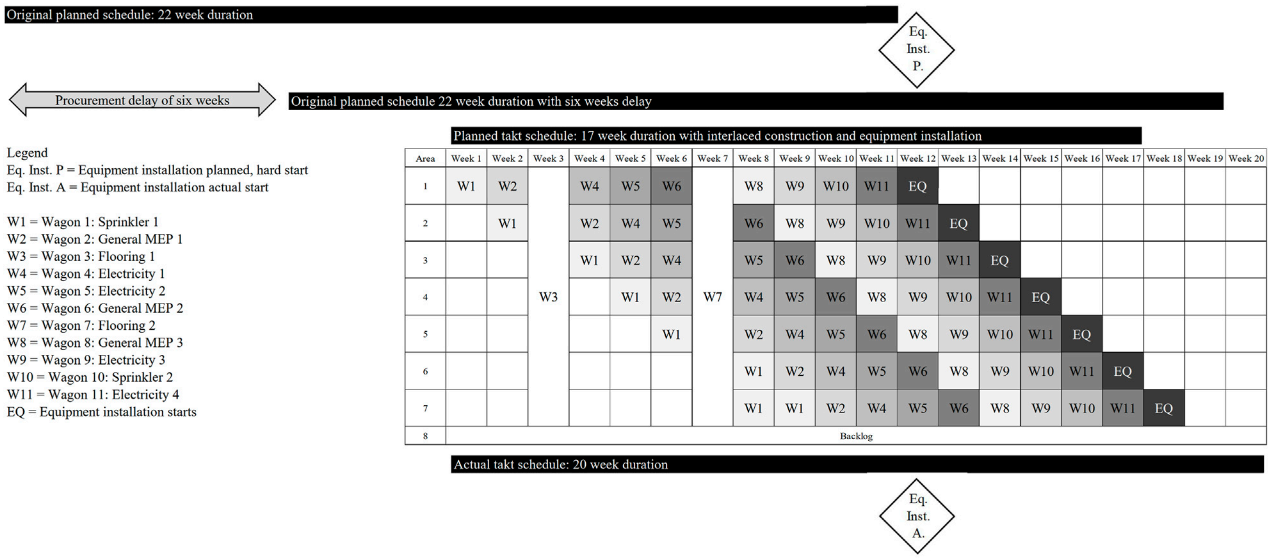

FIGURE 2
Implementation impact on project schedule performance.

in the interior phase for 2 weeks. Despite these challenges, the implementation achieved the desired schedule goals. The challenges required aggressive implementation of the control mechanisms and overtime work, causing a slight cost increase. However, this is not uncommon for first takt production implementation initiatives. Nevertheless, meeting the initial deadline was perceived as having more weight than the minor increase in construction costs.

Qualitative findings and sources of information regarding the implementation and expert workshop validation are presented in Table 3. In the takt planning phase, the framework implementation was perceived as yielding several benefits from both managers' and site teams' perspectives. The implementation process was seen to successfully employ decentralization drivers, such as increasing transparency and trust, which supported effective planning and utilization of site teams' knowledge and increased the plan's process and operations flow. In particular, the crew leaders' knowledge was regarded as beneficial in the process, particularly when coordinating the detailed work within and between wagons (interviewees I15, I16). These results were seen to contribute positively to worker well-being, collaboration within and between teams, and general production performance. The interviewees pointed out that the teams and team members had inherently good chemistry, which partially eased achieving these benefits. In contrast, slightly better worker involvement and more planning resources were suggested as primary development actions. However, providing even more resources for planning can also have adverse effects; acquiring site teams even earlier from their previous projects may not be possible due to resource constraints.

In the takt control phase, the weekly control meetings were experienced as highly beneficial and productive, leading the managers and crew leaders to collaborate effectively and implement swift adjustments when needed. Good site team dynamics created positive competition between the teams, urging them to keep the promised pace (I16). In contrast, one of the most prevalent drawbacks was the workers' seeming lack of participation in the decision-making process during takt control. The scheduled daily meetings were not held consistently, and takt control actions were mainly decided during weekly meetings that only the managers attended. The workers felt uninvolved, causing them stress. Several interviewees recognized this drawback (e.g., I6, I7, I8, I11, I13, I15) and pondered that deeper participation would have led to better collaboration and communication between individual members of collaborating teams. The lack of involvement also posed a barrier to thoroughly examining the effects of decentralization in the control phase.

The elements of good process flow were present quite clearly for most of the production duration, especially flow conditions P1–P3 and P8. However, a slight deterioration of process flow was observed in the beginning and ending stages of the implementation (specifically P4, P5, P7, and partially also O2). Regarding operations flow (O1–O2), the tracked resource needs of trade crews remained relatively stable and were mostly similar to or less than what was planned. With a highly predictable workload (I7, I13), the implementation resulted in good operations flow and a low amount of waiting time. For general MEP work, the resourcing was less than expected for most weeks; yet, the tasks were completed on time without a significant need for over-resourcing.

TABLE 3 Summary of the implementation results.

Implementation positive effects	Challenges and improvement suggestions
1a and 1b Takt planning	
The site teams' knowledge helped improve the plan's process and operations flows (*interviewees I4, I5, I11, I15, I16*).	Decentralized decision-making was partially dominated by the crew leaders; better involvement of workers is needed (*I2, I6, I16, planning session observation*).
The site teams were committed to the formed plan, and both crew leaders and workers (*I1, I2, I3, I4*) and managers (*I11, I12, I13*) had adequate resources and time for the preparation of work.	Decentralized planning requires the swift adaptation and absorption of information; even more time and resources for decentralized planning is needed (*I2, I11, I16*).
The planning process helped the team-building process, increasing transparency and trust between the site personnel (*I1, I2, I3*); a structured and detailed approach with timely involvement fostered effective and collaborative planning (*I13, I15, I16, I17, planning session observation, expert workshop feedback*).	The role of logistics planning should be increased in the planning phase (*I1, I2, I3, I11, expert workshop feedback*).
Tailored framework for the given situation supported implementation (*expert workshop feedback*).	—
2 Takt control and 3 Continuous improvement	
Effective collaboration, communication, and problem-solving between managers and crew leaders, especially through weekly meetings (*I4, I7, I13, I15*).	Lacking participation of workers in decision-making; more effort is needed on following the decentralized process promptly, ensuring the possibility for participation (*I6, I7, I8, I11, I13, I15, meeting minutes and meeting observation, expert workshop feedback*).
Adequate involvement and awareness were enabled by the intensive planning process, enabling swift adjustment of the plan when needed (*I11, I13, I13, I17*).	Inadequate involvement of workers caused stress for site teams (*I3, I4, I5, I6*); more resources for onboarding and training of workers were needed to ensure commitment (*I16, I17*).
Good site team social dynamics and positive competition between teams (*I16*).	The role of logistics control should also be increased in the control phase (*I12, I13, expert workshop feedback*).
Effects on flow	
Process flow: effective production planning, wagon handoffs, and a "ready with first-time attitude" helped achieve and maintain a good overall process flow; work was primarily in balance (process flow condition P1); the site teams respected the distribution of takt areas and takt times while primarily operating with the determined batch sizes (P2). This resulted in small WIP (P8) and small time buffers (P3), as tasks began after the preceding one ended (*I7, I15, project diary, meeting minutes*).	Process and operations flow: slight deterioration of flow at the beginning and end stages of the interior phase due to intensity of ramp-up (*I2, I16*), inadequately adjusted project phase interphases (*I4, I5, I6*), missing JIT logistics management (*I6, I7, I11*), and partial reliance on ad hoc management practices in the final weeks (*I11, I13*) resulted in a partially increased number of unnecessary activities (P4), re-entrant flow (P5), making-do (P7) and set-up times (O2).
Operations flow: primarily good operations flow (O1 and O2); low amount of waiting, stable resource needs (*I2, I3, meeting minutes, resource tracking*), predictable workload (*I7, I8, I11, I13*),	—

The general MEP works team observed that the tasks outside the interior phase (e.g., rainwater piping) resulted in slight resource fluctuation in the beginning, as the overlapping resource needs between the structural and interior phases were not considered in the takt plan (I4, I5). This highlights the importance of alignment between production phases, including those not part of the takt production implementation. In hindsight, general MEP team members recognized the alignment as a critical part of planning, especially as they had a large amount of work in other phases, affecting their task sequencing and resourcing. Simultaneously, an extended collaboration between teams operating in different production phases was seen as an improvement opportunity for better overall communication and collaboration (I5). For electricity, increased resources were needed in the end, but the electricity manager and the site team stated that the workload was still adequate and more predictable than usual, with an increased opportunity to affect their work sequencing (I7, I8, I11). The electricity team (I2, I3) reported that their operations flow was excellent compared with a traditional project as they could work independently in their reserved takt areas right from the start. Electricity team members were not accustomed to having space and time for their tasks, which are often scarce in traditional projects.

Discussion

Implementation synthesis

Overall, the results indicate that decentralized decision-making is suitable to be combined with takt production, resonating with previous findings of combining takt production with other decentralized approaches (e.g., Frandson et al., 2014). Observed from the case and the expert workshop results, the framework's implementation was primarily perceived as successful and yielding many lessons. In particular, the framework contributed positively to schedule performance (the implementation helped to achieve 23% duration savings in the interior phase) with interlaced construction and handover, with similar results to Dlouhy et al. (2017). Takt planning (where the participants' involvement was done granularly while transitioning from high-level to decentralized planning) was regarded as positively contributing to overall flow while advancing the drivers of decentralization, such as the site teams' increased commitment and decision-making power. Increased process flow after finding the production rhythm (Lehtovaara et al., 2021), the ability to solve emerging problems collaboratively and proactively (Frandson et al., 2014), and better control over production duration (Binninger et al., 2017) were also observed in the case at hand. Process transparency and increased plan reliability were documented as well, stemming from the benefits gained by previous decentralized PP&C implementations (Priven and Sacks 2015).

Takt control faced some implementation problems, while flow defects were experienced in the beginning and slightly at the end of production (similarly noted by, e.g., Lehtovaara et al., 2019). Similar to previously documented takt production cases, the increased role of logistics management, more intense involvement of trade crews in management practices, and increased efforts to ramp-up (e.g., Frandson et al., 2013), were also suggested as development actions in our case and expert workshops. These results appear to be quite usual for first-time takt production implementations (e.g., Lehtovaara et al., 2021), indicating that although the decentralized approach yields some unique benefits and concerns, all takt production approaches seem to have certain similar benefits to flow, especially process flow.

However, in contrast to other first-time takt implementation cases in which results for operations flow have often been ambiguous (e.g., Frandson et al., 2013; Alhava et al., 2019), the interview, meeting minute, and resource tracking data indicate that the operations flow conditions were perceived to improve in the case at hand. Adequate preparation in the planning stage and the teams' early involvement in decision-making (e.g., Chinowsky et al., 2010) built trust through the production (see also Humphrey et al., 2007; Yang and Guy, 2011), initiating healthy competition between site teams and helping them prepare for their work effectively. Adequate preparation and early involvement also eased the recognition of site teams' responsibilities during the (decentralized) planning (e.g., Bertelsen and Koskela, 2005) and in decision-making overall (e.g., Saurin et al., 2013), helping in obtaining the intended benefits and aiding in maintaining good operations flow during the production.

Improvement avenues for decentralizing decision-making in takt production

Despite these promising results, certain challenges and areas for improvement were also found for combining decentralized decision-making with takt production. Some of the drivers and expected benefits, especially those related to workers' personal performance, were not realized, partially due to inadequate implementation of the decentralized practices in the control phase. For example, although decentralized planning positively contributed to the site teams' commitment and motivation (Richardson et al., 2002), these elements were not observed during takt control as the decisions were primarily made at the managerial level. The control phase operated more in a centralized than a decentralized manner. The managers performed more as decision-makers than facilitators, while the teams were not empowered to act autonomously (contradicting decentralization drivers, e.g., Saurin et al., 2013; Magpili and Pazos, 2018). Lehtovaara et al. (2022) similarly observed that decentralized practices are often limited to the managerial and/or crew leader levels, which might result in inconsistencies between different decision-making levels and hamper the possibilities of improving management practices and overall flow. The expected drawbacks of decentralization, such as inconsistent coordination between teams (Stinchcombe and Heimer, 1985) and inconsistent knowledge sharing (Mintzberg, 1983), were surprisingly not caused by decentralized decision-making but rather due to the lack of it. However, it should be noted that these drawbacks were not largely present. The project's relatively small size and the initial transparency between its participants seemed to help overcome the disadvantages, which are especially prone to occur in large-scale and complex projects (Leavitt, 2005).

Although the external challenges (e.g., the COVID-19 pandemic that hampered the possibility for active framework implementation facilitation in the control phase) had a certain effect in terms of failing to extend the decentralization to the worker level in the control phase, it seems that successfully implementing all aspects of decentralization would nevertheless require a systematic effort over single projects (also Lehtovaara et al., 2022). Increasing the role of decentralized decision-making in the control phase would most likely require comprehensive cross-project and cross-organizational improvement and training of project participants to empower site teams with autonomy (e.g., Magpili and Pazos, 2018) and to train site managers to act better as facilitators (e.g., Saurin et al., 2013). With the existing management culture and practices, slipping into familiar, centralized production control is easy, even when decentralization would be viewed as a welcome change, as widely admitted by the study participants. These assumptions also resonate with a takt production maturity model (Lehtovaara et al., 2020), suggesting that succeeding in takt planning is relatively easy in the first implementation cases, but adopting the principles of takt control and adequate collaboration throughout the project often requires experience over several implementation attempts. It seems that the same progress toward higher maturity levels is present in decentralized takt production as well, further supporting the idea that takt production and decentralization share synergy advantages; however, further validation is needed to draw any definite conclusions. Also, the general experience of the teams should be considered when interpreting the results. Teams with greater experience, a background working with each other, and the ability and willingness to use innovative methods might possess a particular advantage in implementing novel approaches such as decentralized decision-making and takt production. In this case, although inexperienced with takt production, the site managers and teams felt generally positive toward the implementation, which should be considered when interpreting the results against future implementation cases.

Conclusion

Concluding notes and study contribution

In this study, we employed a design science research (DSR) approach to formulate, implement, and validate a PP&C framework that allowed us to evaluate the effect of decentralized takt production on production performance and flow. The studied framework considered the combined implementation of decentralized decision-making and takt production, including the viewpoints of site teams and first-line workers, which have been lacking in previous research initiatives. The results provide novel theoretical and practical contributions regarding both takt production and decentralized planning and control in the context of construction production flow management. Considering the RQ *How could combining takt production with decentralized decision-making affect construction PP&C practices and production flow?* We have observed that decentralization is suitable to be combined with takt production, aiding overall flow and schedule performance, even in a project where participants had no previous experience with takt production. Good operations flow was found to be especially supported by decentralized decision-making and the implemented decentralization drivers. These positive effects on flow were further supported by, e.g., observations on improved utilization of site teams' knowledge in planning, better commitment, communication, and team-building processes (further leading to increased transparency, trust, and problem-solving capacity), and positive competition between teams. The interior phase also achieved a 23% duration savings with interlaced construction and equipment installation, and stable resource utilization of trades. The decentralized decision-making practices were successfully implemented in the planning phase; however, the elements of decentralization were not adequately utilized in the control phase, resulting in the benefits not being obtained to their full potential magnitude.

For further implementation of decentralized takt production, the most critical improvement suggestions are as follows: 1) more systematic and cross-organizational involvement and training of decentralization principles should be ensured to empower site teams to act as autonomous decision-makers and managers to serve as facilitators; 2) more extensive training and implementation of takt production practices should be ensured for project participants, focusing on effective ramp-up and daily production control in which site teams (including workers) can actively participate; and 3) the role of logistics management should be improved, for example, by involving material suppliers and logistics operators in the decentralized PP&C processes. Notably, the suggestions for improvement are weighted toward training the participants and developing their understanding of takt production and decentralization practices. It seems that an extensive effort over single projects and organizations is needed to gain all intended benefits, while the competence to successfully operate with (decentralized) takt production increases with experience.

Study limitations and avenues for future research

Although the wide range of collected evidence offered a possibility to explore decentralized takt production in depth and increase the study's validity (Eisenhardt and Graebner, 2007), the setting of a single-case study has limitations for generalizability. Moreover, as the expert workshops were conducted with a pool of experts who were already interested in applying decentralized planning and control, confirmation bias toward the framework's benefits possibly exists, although the implementation challenges and adverse effects were also widely discussed. As the framework development was guided by iteration that considered the specific implementation situation, the utilization of the framework in different contexts should be supported by fitting the framework for the given setting. However, the perceived effects on flow could be considered rather universal, so they could be seen at least as a basis for evaluating the effects of decentralized takt production in other geographical locations, project types, or organizations.

Furthermore, the explorative findings were based on a combination of qualitative and quantitative data, which did not allow for assessing and comparing the quantity of flow effects unambiguously. Future research could validate the impact of decentralized takt production compared to other takt production and other PP&C approaches (such as LBMS) through a comparative, multi-case, quantitative analysis. However, one should bear in mind that even in multiple-case study settings, comparing the results might not provide unambiguous conclusions. The assessment of a schedule performance is always subject to the project's external and internal factors and the quality of the initial planning. Factors such as managers' and teams' experience, management style, and leadership attributes can affect how decentralized decision-making and takt production implementation can succeed. Moreover, longitudinal effects of the approach, particularly in cases with higher takt production maturity, could be considered as future research initiatives. It could also be explored how spatiotemporal planning, providing a computer-aided and automated approach, would affect decentralized takt production performance. Finally, in future research, a framework calibrated more explicitly toward pure decentralization could be interesting to implement; however, to succeed, it might need the aforementioned high maturity and/or remarkably increased effort and capacity to drive the process toward pure decentralization of PP&C.

Data availability statement

The datasets presented in this article are not readily available due to privacy restrictions. Requests to access the datasets should be directed to JL at joonas.lehtovaara@aalto.fi.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements.

Author contributions

JL conducted the study design with the assistance of OS. JL and EL conducted the data collection and analysis. JL conducted the literature review, prepared the first draft of the manuscript, and finalized the manuscript. All authors (JL, EL, OS, AP, and PU) participated in revising and editing. All authors have read and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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