Lappalainen, E., Peltokorpi, A., & Seppänen, O. (2026). Catalysts for learning and innovation in Takt production. In F. Hamzeh, M. Poshdar, N. P. Garcia-Lopez, & V. Gan (Eds.), *Proceedings of the 34th Annual Conference of the International Group for Lean Construction* (IGLC34) (pp. 668–679). https://doi.org/10.24928/2026/0122

CATALYSTS FOR LEARNING AND INNOVATION IN TAKT PRODUCTION

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ABSTRACT

Takt production (TP) emphasizes enhancing flows and minimizing inventories in alignment with fundamental principles of lean thinking. Nonetheless, the significance of slack in TP has been acknowledged. This aligns with the prevailing view of system dynamics, which underscores inventories as a stabilizing factor in addition to flow regulation. This study investigates the influence of learning and innovation on TP research, as well as the relationship between TP and inventory. The intrinsic sluggishness of inventories facilitates safer experimentation from a learning and innovation standpoint. Moreover, diverse forms of slack enhance the stability of the TP system amid ongoing improvement and learning. This study indicates that learning and innovation play a crucial role in successful TP; however, the literature review reveals that existing research has not thoroughly examined their role in this context, suggesting the need for further research. The study also categorizes six catalysts that support learning and innovation in TP: work design and production logic; feedback loops, control, and continuous improvement; culture, collaboration, and shared meaning; learning capabilities and mechanisms; digital infrastructure for learning and innovation; and structural and contractual enablers, with the latter two identified as under-researched. This paper delineates methodologies for learning and innovation applicable to TP.

KEYWORDS

Lean Construction, Takt production, learning, innovation, catalysts.

INTRODUCTION

Key elements in systems include stocks, flows, feedback loops, delays, and interdependencies. A stock is a store or supply accumulated or available, especially inventory, and a flow is the issuance or movement in a stream, usually to or from the stock with a delay, regulating it (Meadows, 2008). When a stock rises in leaps, falls rapidly, or remains within a certain range, regardless of what else is happening around it, this is likely a feedback loop (Meadows, 2008). A feedback loop is formed when interdependent inflows and outflows affect changes in the stock.

The role of stocks as catalysts for learning and innovation has received limited attention in current takt production (TP) research. Existing studies have primarily focused on flow efficiency, buffer management, and operational performance, while the dynamic role of stocks in enabling experimentation, innovation, and learning remains underexplored. Therefore, this study addresses this gap by examining how learning and innovation are conceptualized in the

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TP literature, with particular attention to the role of stocks. The research question is as follows: *What catalysts for learning and innovation are conceptualized in the literature on takt production?*

STOCKS IN RELATION TO LC CONCEPTS

In this study, we distinguish between key terms to ensure conceptual clarity across system dynamics and lean construction (LC) perspectives. In system dynamics, *stock* is used as a general term for accumulation within a system (Meadows, 2008). However, in LC, more specific distinctions are made: *inventory* refers to material accumulation, including work-in-process (WIP; Lehtovaara et al., 2021); *buffers* denote mechanisms used to absorb variability, which may take the form of time, capacity, or material buffers (Fireman et al., 2023); and *slack* refers to excess time or capacity available to accommodate disruptions (Formoso et al., 2021). In the context of TP, these concepts are typically operationalized as WIP (inventory/material stock) and time or capacity buffers (slack), linking the system dynamics construct of stock to observable practices in TP (Lehtovaara et al., 2021). However, slack should not be understood solely in terms of buffers. It may also be conceived more broadly as organizational and managerial flexibility for coping with complexity (Formoso et al., 2021). In addition to explicit time and capacity buffers, slack may take the form of opportunities for parallel work despite differences in design timing, or the ability of site management staff to substitute for one another in coordination activities.

Stocks evolve gradually despite significant variations in flow (Meadows, 2008), constituting their fundamental nature. This positions stocks as shock absorbers within the system. Individuals may misjudge the inertia of stocks and alter the flow before they have had time to respond. This phenomenon is familiar to most people from heating or cooling systems in their homes. A further illustration is a widely recognized transformation in business: the implementation of new methodologies invariably necessitates more time than anticipated, since individuals require time to acquire new knowledge. In the construction context, such instances of sluggish stocks include the painfully gradual depletion of unsold apartments on the balance sheets of construction firms during economic downturns.

Interesting aspects of stocks are their inherent slowness and the buffers they generate, which can be leveraged for learning and experimentation. When sufficient stocks (e.g., material inventory, space, time) are available, errors do not jeopardize the entire project, active experimentation does not significantly hinder production, and new methodologies can be tested without imminent risk (e.g., contractual penalties, delays). Conversely, in a production model that functions with minimal or no slack, every aspect is crucial, implying that innovation, progress, and experimentation may not be actively promoted. From a systems thinking viewpoint, this system is fragile (Meadows, 2008). Therefore, several recommendations have been applied to TP, whereby each takt should include a 15–20% capacity buffer, and any surplus time should be allocated for development (Lehtovaara et al., 2023).

LC research has studied both flows and stocks, including TP, buffer management, and slack (Formoso et al., 2021). Several buffers are extensively employed in LC to maintain TP balance, including time and resources (Fireman et al., 2023). Although the notion of buffers and their implementation in TP is well established, the significance of stock slowness has been inadequately addressed in relation to innovation and learning. For example, Lehtovaara et al. (2021) acknowledged the significance of continuous improvement and learning in TP, although they did not identify these as characteristics of buffers but rather as factors associated with organizational maturity. Frandson (2019) similarly underscored the importance of learning, linking it to the capacity of work teams to acquire knowledge through repetition in TP. Binninger et al. (2018) contended that reduced lead times in TP facilitate an accelerated learning

curve. All of these characteristics are tangible; however, they fail to acknowledge the systemic and dynamic role of stocks as a crucial element in learning and innovation (Meadows, 2008).

This is understandable, as the construction sector has shown growing interest in improving flow, likely due to the rapid, easily detectable, and tangible changes in flow, whereas stocks evolve more slowly, making changes slower to identify in a complex and fast-paced project environment (Lehtovaara, 2023). Rapid changes are characteristic of project-based enterprises, and the construction industry is no exception. From this viewpoint, the emphasis of LC practitioners and scholars on flow, which may be more attractive to observe and measure, appears rational. This emphasis may also stem from the ideological perspective on inventory in lean methodology, which posits that it should be fundamentally eliminated (Fireman et al., 2023).

Following the literature review, this paper briefly outlines the primary themes of learning and innovation in TP research, thereby developing a focused synthesis and identifying significant gaps despite the space and time constraints of this short conference paper. The paper concludes by examining how the learning and innovation catalysts identified in the literature may open new frontiers for learning and innovation in TP.

METHODOLOGY

This study adopted a systematic literature review as its research method. This method is appropriate for a brief conference paper because it facilitates a rapid, adaptable, and coherent synthesis of the literature (Nightingale, 2009). The review was based on search terms appropriate for identifying relevant academic publications in the Scopus, Google Scholar, and International Group for Lean Construction (IGLC) databases. A systematic literature review was conducted by querying these three databases for papers pertaining to takt production, slack, and buffers. The initial search was conducted on Google Scholar using the search terms "lean construction" AND "takt production" AND “buffer” OR “slack”, resulting in 110 papers. A search was subsequently conducted in the Scopus database using the search term TITLE-ABS-KEY ("lean construction" AND "takt production" OR “slack” OR “buffer”), resulting in 51 papers. The final search was conducted in the IGLC.net database using the term "takt," resulting in 129 documents. All documents were organized in a table, and their number of citations was assessed via Google Scholar. The Pareto principle was applied to prioritize the most influential and widely cited contributions, and articles that together accounted for approximately 80% of total citations were selected. This ensured that the analysis focused on the most influential and representative body of journal and conference articles on TP, buffers, and slack while maintaining feasibility within the constraints of a conference paper format.

The included articles underwent thorough analysis, with each item accessed and a text search conducted using the terms "learn*" and "innova*". If these terms were present in the document, the corresponding sections were examined to identify the elements recognized as catalysts for learning and innovation in TP. During this phase, 24 articles were identified that did not contain the term "takt," despite the initial search parameters. Because this study specifically focuses on TP, these articles were excluded from further analysis. To maintain the dataset size, the excluded items were replaced with subsequent articles in the citation-ordered dataset that explicitly referenced takt. This procedure ensured that the analyzed dataset consisted of articles that explicitly addressed TP while maintaining the originally targeted sample size.

Among the remaining 34 publications addressing TP, 22 explicitly delineated catalysts for learning and innovation in relation to TP. The identified catalysts were subsequently grouped into six categories using an inductive thematic coding approach (Proudfoot, 2023). Recurring patterns and conceptually similar elements across the analyzed articles were clustered together,

and the resulting groups were iteratively refined to ensure internal consistency and conceptual distinctiveness.

FINDINGS FROM THE LITERATURE

Based on the literature review, catalysts for learning and innovation in TP can be divided into the following categories: 1) work design and production logic, 2) feedback loops, control, and continuous improvement, 3) culture, collaboration, and shared meaning, 4) learning capabilities and mechanisms, 5) digital infrastructure for learning and innovation, and 6) structural and contractual enablers. These are shown in Table 1.

Table 1: Catalysts for learning and innovation in Takt production

Catalyst for learning and innovation	Group	Source
High early workload	Work design, and production logic	#1: Frandson et al. (2013)
Novelty of work	Learning capabilities and mechanisms	
Encouragement to consider alternative perspectives	Learning capabilities and mechanisms	
The degree of precision in planning necessitates an elevated level of experience and knowledge	Learning capabilities and mechanisms	
Organizational support	Culture, collaboration, and shared meaning	
Continuous mentorship and interaction – "learning while doing"	Culture, collaboration, and shared meaning	
Supporting personal growth and well-being	Culture, collaboration, and shared meaning	
Learning across all roles	Culture, collaboration, and shared meaning	
Deliberate underload as a foundational requirement for innovation	Work design and production logic	#2: Frandson et al. (2015)
Time buffer for experimentation and development	Work design and production logic	
"Off takt" work as a learning environment	Work design and production logic	
Linking learning to work development	Digital infrastructure for learning and innovation	
Waiting for the last responsible moment	Work design and production logic	#3: Frandson et al. (2014)
Continuous flow of work	Work design and production logic	#4: Linnik et al. (2013)
Shared understanding through dialog	Culture, collaboration, and shared meaning	#5: Tommelein (2017)
High number of quality checks due to short takt time	Feedback loops, control, and continuous improvement	#6: Binninger et al. (2018)
Man-minutes per unit produced as a reflective metric over projects	Feedback loops, control, and continuous improvement	#7: Heinonen & Seppänen (2016)
Learning throughout the value chain – not just on the construction site	Culture, collaboration, and shared meaning	#8: Lehtovaara et al. (2019)
"Softer start" as an enabler of innovation	Structural and contractual enablers	
Thorough planning as an enabler of innovation	Structural and contractual enablers	
Transparency as a catalyst for innovation	Digital infrastructure for learning and innovation	
Digital tools as infrastructure for innovation		
Common understanding as a condition for innovation	Digital infrastructure for learning and innovation	
Onboarding and digital adoption as innovation scalers	Culture, collaboration, and shared meaning Digital infrastructure for learning and innovation	
Organizational maturity	Learning capabilities and mechanisms	#9: Lehtovaara et al. (2020)
Collectivity	Culture, collaboration, and shared meaning	
Contractual integration	Structural and contractual enablers	
Thinking across projects	Culture, collaboration and shared meaning	
Standardized workload libraries	Structural and contractual enablers	
Use of key performance indicators	Feedback loops, control, and continuous improvement	

Table 1: Catalysts for learning and innovation in Takt production - continued

Catalyst for learning and innovation	Group	Source
Plan–do–check–act process	Feedback loops, control, and continuous improvement	#10: Lerche et al. (2022)
Visibility of deviations	Feedback loops, control, and continuous improvement	
Widely shared learning	Culture, collaboration, and shared meaning	
Common language and visuals, shared semantic system	Culture, collaboration, and shared meaning	
Differentiating teams	Learning capabilities and mechanisms	
Managing variation	Feedback loops, control, and continuous improvement	
Transfer learning from downstream to upstream	Culture, collaboration, and shared meaning	
Performance measurement	Feedback loops, control, and continuous improvement	#11: Chauhan et al. (2018)
Situational awareness	Learning capabilities and mechanisms	
Knowledge from established industries	Learning capabilities and mechanisms	#12: Tetik et al. (2019)
Digital situational awareness	Digital infrastructure for learning and innovation	#13: Alhava et al. (2019)
Training	Learning capabilities and mechanisms	
Simulations	Learning capabilities and mechanisms	#14: Tsao et al. (2014)
Hands-on activities and pull planning games	Learning capabilities and mechanisms	
Assumptions on resource availability and productivity data	Structural and contractual enablers	#15: Emdanat et al. (2016)
Engaging those accountable for the task prior to execution	Learning capabilities and mechanisms	
Collaboration	Culture, collaboration, and shared meaning	
Real-time control	Feedback loops, control, and continuous improvement	
Slack at work – in time, resources, or capacity	Work design and production logic	#16: Fireman et al. (2023)
Simplification of product design	Work design and production logic	
Incremental improvement	Feedback loops, control, and continuous improvement	
Consciously learning system	Learning capabilities and mechanisms	#17: Kalsaas et al. (2014)
Control	Feedback loops, control, and continuous improvement	
Deviation visibility – causal analysis from breakdowns	Feedback loops, control, and continuous improvement	
Small batch sizes	Work design and production logic	#18: Tommelein & Emdanat (2022)
Strict sequence of work	Work design and production logic	#19: Moura et al. (2014)
Repetition of work	Work design and production logic	
Small batch sizes	Work design and production logic	
Repetition of work	Work design and production logic	#20: Dlouhy et al. (2019)
Freeing up the manager's time	Learning capabilities and mechanisms	#21: Tommelein (2020)
Monitoring work by observation	Feedback loops, control, and continuous improvement	
Simple frameworks to support learning	Feedback loops, control, and continuous improvement	
Digital situational awareness	Digital infrastructure for learning and innovation	#22: Halttula and Seppänen (2022)
Learning through data	Feedback loops, control, and continuous improvement	

The identified catalyst categories can be understood as complementary dimensions that together enable learning and innovation in TP. At the operational level, work design and production logic structure processes and sequencing (e.g., takt time and different flows), creating the transparency and predictability required for learning. These are reinforced by feedback loops,

control, and continuous improvement mechanisms, which allow performance to be monitored, deviations identified, and processes systematically developed. At the social level, culture, collaboration, and shared meaning shape the conditions—such as trust, communication, and shared understanding—that support collective learning and knowledge exchange.

Building on these, learning capabilities and mechanisms describe organizational practices such as reflection, experimentation, and knowledge transfer, through which new knowledge is generated and applied. These processes are increasingly supported by digital infrastructure for learning and innovation, including tools for data collection, analysis, and visualization. Finally, structural and contractual enablers provide an organizational and governance context that enables collaboration, flexibility, and innovation.

SUMMARY OF CATALYSTS OF LEARNING AND INNOVATION IN TAKT PRODUCTION

This study examines the conceptualization of learning and innovation in TP. This section summarizes academic understanding of catalysts for learning and innovation in TP based on the literature. The literature search is categorized into six catalyst groups, as follows.

1. WORK DESIGN AND PRODUCTION LOGIC

This category of learning and innovation in TP was identified already in the early TP literature. Frandson et al. (2013) highlighted the complexity of TP design as a context that supports learning about different methods, while also linking team learning to a growing need for support from designers. Early TP research also associated learning with the need to support personal development and well-being. Another early finding was that workload plays a central role in learning in TP. Frandson et al. (2014, 2015) emphasized underload and the last responsible moment as enablers of invention, whereas Moura et al. (2014) argued that tighter schedules promote learning. Linnik et al. (2013) linked workflow continuity with continuity of learning, suggesting that frequent interruptions disrupt both. This contrasts with Frandson et al. (2015), who argued that deceleration of flow, such as finishing some tasks early, creates opportunities for preparation, training, research, and innovation. Dlouhy et al. (2019) further warned that uninterrupted repetition may lead to overly simplistic routines, while Fireman et al. (2023) and Tommelein and Emdanat (2022) suggested that a reduced batch sizes enhance learning and incremental innovation. Overall, the literature reveals a tension between strict flow control and the slack needed to enable learning, and the relationship between flow efficiency and learning remains unresolved.

2. FEEDBACK LOOPS, CONTROL, AND CONTINUOUS IMPROVEMENT

Feedback loops, control, and continuous improvement—the core components of systems—have been recognized as catalysts for learning and innovation in TP research since its inception. Early TP studies emphasized control and direction as mechanisms for reinitiating planning in TP (Kalsaas et al., 2014), but later research has developed this view further. For example, Binninger et al. (2018) linked more frequent quality control inspections to a steeper team learning curve. Several studies have also highlighted the role of quantitative measurements within feedback loops, suggesting that their systematic evaluation can support learning (Chauhan et al., 2018; Emdanat et al., 2016; Halttula & Seppänen, 2022; Heinonen & Seppänen, 2016; Lehtovaara et al., 2020). In addition, Lerche et al. (2022) showed that integrating the plan–do–check–act cycle with Kanban connected the visibility of variation with learning from past events, including deviations. Tommelein (2020) likewise argued that observation, evaluation, training, and the support of professional development can enhance workplace learning. Despite this emphasis on feedback mechanisms, literature still largely assumes rather than demonstrates how they lead to actual learning outcomes in TP. Empirical evidence linking

performance measurement and feedback loops to concrete learning processes therefore remains limited.

3. CULTURE, COLLABORATION, AND SHARED MEANING

Learning in TP has also been linked to the role of the main contractor. Frandson et al. (2013) argued that main contractors must support individuals at all organizational levels in TP project. In this context, simply distributing takt plans is not enough; TP requires a collaborative approach that builds consensus through team discussions (Tommelein, 2017). This also demands that individuals adopt novel ways of collaboration. Lehtovaara et al. (2019) emphasized the importance of a gradual start and a comprehensive planning phase involving all stakeholders. They also highlighted mutual understanding as a prerequisite for learning and noted that much of the learning concerns design activities, including production staff gaining insight into designers' perspectives and challenges. In contrast, Lerche et al. (2022) suggested that teams should be separated during takt planning for safety reasons and to improve learning from deviations, while framing safety as a universal language in TP. Overall, the reviewed literature offers differing views on how collaboration should be structured in TP, particularly regarding team integration versus separation, and provides limited explanation of how these cultural and social factors are operationalized in takt-controlled environments.

4. LEARNING CAPABILITIES AND MECHANISMS

The significance of learning capabilities and mechanisms was recognized early in TP research as a catalyst. Frandson et al. (2013) proposed that learning capability is closely linked to the personal development and well-being of employees and management, which the main contractor should endorse to achieve improved management of daily production. The same assertion was subsequently articulated by, among others, Tommelein (2020). Kalsaas et al. (2014) and Lerche et al. (2022) suggested that learning capacity is associated with a stimulus arising from situations in which actions diverge from the intended plan—a form of learning activated by problems. Lerche et al. (2022) agreed on the role of deviations and positive observations as a method for learning.

Tsao et al. (2014) proposed a teacher–learner approach that enhances community learning through simulations. Lehtovaara et al. (2020) proposed a similar approach to collective learning and linked it with organizational maturity as a method for enhancing learning. Tetik et al. (2019) expanded the field of learning in TP more broadly and emphasized the importance of learning from other fields, such as logistics and shipbuilding.

Alhava et al. (2019), Chauhan et al. (2018), and Emdanat et al. (2016) offered a technocratic perspective on learning. These studies emphasized the significance of real-time measurement and automated situational awareness within learning mechanisms.

While learning capabilities are highlighted as important, the reviewed literature varies between human-centered and technocratic perspectives, without clearly integrating these viewpoints. As a result, the mechanisms through which learning capabilities translate into improved TP performance remain insufficiently specified.

5. DIGITAL INFRASTRUCTURE FOR LEARNING AND INNOVATION

The significance of digital infrastructure for TP learning has risen in recent years due to technological advancements. Lehtovaara et al. (2019) asserted that digital tools possess significant potential, particularly in strengthening the learning process. Alhava et al. (2019) described the advantages of a digitalized construction site in their study, highlighting the disciplined application of these tools and, conversely, a pragmatic approach to resource-related learning. Alhava et al. (2019) introduced a methodology for assessing digital learning, utilizing the outcomes of the activity matrix to track individuals' learning curves.

However, despite the enthusiasm for digitalization, Halttula and Seppänen (2022) noted the absence of research regarding the impact of digital tools—such as situational awareness systems—on learning in TP. Overall, despite increasing interest, the role of digital infrastructure in enabling learning and innovation in TP remains underexplored and lacks robust empirical validation.

6. STRUCTURAL AND CONTRACTUAL ENABLERS

According to the literature review, structural and contractual enablers have garnered less attention in TP research as a learning catalyst. Only Lehtovaara et al. (2019, 2020) concentrated on these issues. The correlation between mutual understanding and advances in organizational maturity in TP are associated with enhanced integration in contracting (Lehtovaara et al., 2019, 2020). Emdanat et al. (2016) proposed that cooperation founded on mutual understanding enhances the alignment between resource assumptions and actual work performance, facilitating the early identification of risks associated with project production among contractual parties. This suggests a gap in the research, as the role of contractual and structural arrangements in enabling or constraining learning and innovation in TP has received very limited attention.

Overall, the literature on learning and innovation in TP remains fragmented and unevenly developed. While numerous catalysts have been identified, their interrelationships and underlying mechanisms have rarely been examined in an integrated manner. In particular, tensions between control and flexibility, as well as gaps related to digital and contractual enablers, indicate that the current understanding of learning and innovation in TP is still conceptually and empirically incomplete.

DISCUSSION

As mentioned earlier, in systems thinking, two essential concepts are fundamental to learning and innovation: 1) a reserve of slow variables facilitates secure learning and innovation and 2) flexibility emerges when the system can "accommodate" learn-by-failure through its stocks. Stocks can be regarded as elements of system inertia, which contributes to its stability. Experiments conducted within suitable limits typically do not surpass the system's stability, and faults do not rapidly propagate between processes, thereby preventing system failure. This may be seen as a fundamental aspect of a learning organization (Lehtovaara et al., 2020).

In the context of TP, these concepts can be understood more concretely through the interaction between WIP, time buffers, and production stability. When limited slack is intentionally incorporated into the system, such as through takt-time allowances or capacity buffers, it reduces the risk of local disruptions propagating immediately across trades (Tommelein, 2020). This may create a controlled environment in which teams can test alternative work methods, reflect on outcomes, and adjust practices without jeopardizing overall flow, as discussed by Halttula and Seppänen (2022) and Lehtovaara et al. (2021). In this sense, stocks and slack may function as enablers of localized experimentation and feedback, supporting learning and innovation within the TP system.

When experimentation capacity is incorporated into the production system, it increases in conjunction with stocks. Conversely, in the absence of innovation stocks, learning is unattainable, and without learning, innovation cannot occur. The system may evolve into an innovation-deficient system if stocks are perceived dualistically along the good–bad continuum as mere waste that must be eliminated from the system (Fireman et al., 2023; Formoso et al., 2021). Therefore, this paper positions stock as a secure environment for the system, facilitating learning and innovation rather than simple waste.

Importantly, a distinction must be made between productive slack and waste. Productive slack refers to deliberately designed buffers that enable adaptation, learning, and recovery from

variability, whereas waste corresponds to unmanaged or excessive accumulation that does not contribute to system performance (Formoso et al., 2021; Fireman et al., 2023). In TP, slack becomes beneficial when it is purposeful, limited, and aligned with production control objectives—for example, when time buffers are used to stabilize flow or to enable continuous improvement activities (Dlouhy et al., 2019; Tommelein, 2020). In contrast, uncontrolled inventory or idle time that does not support learning or system stability should be considered waste. This distinction is critical to avoiding the interpretation of all forms of stock as either inherently beneficial or inherently detrimental.

The significance of learning and innovation as a stock lies in providing a degree of free "breathing space" that can safeguard the production system. In a system equipped with sufficient buffers for learning and innovation, faults do not compromise the integrity of the entire system (or, in construction, the project). Innovation facilitates experimentation (e.g., simulations) and the evaluation of novel methodologies without the imminent threat of disrupting the production system (Tsao et al., 2014). Innovations may also mitigate changes, providing the opportunity to adjust to market fluctuations without immediate detriment to businesses (Fireman et al., 2023; Formoso et al., 2021).

Without a buffer, everything becomes critical in the worst case. Such actions may result in organizations becoming hesitant to innovate and concentrating solely on ad hoc and hands-on manufacturing. An entirely lean-optimized system may be seen as brittle and potentially noninnovative (Meadows, 2008).

Based on this literature review, buffers—such as time, cost, and material buffers—exist and are designed in TP, but their utilization frequently focuses on addressing and anticipating issues and deviations rather than fostering innovation (Dlouhy et al., 2019; Kalsaas et al., 2014; Lerche et al., 2022). This review revealed an inconsistency in attitudes toward these buffers; although some research asserted that a strict timetable facilitates learning (Moura et al., 2014), other studies proposed that a degree of slack promotes learning (Frandson et al., 2014, 2015). According to the reviewed literature, neither of these assertions can be disproven, given that the majority of the information presented in TP studies on learning and innovation is largely anecdotal and lacks empirical validation. The reviewed research suggests that learning and innovation are significant; however, this notion often remained a mere assertion in most studies.

Despite the recognized importance of learning and innovation in TP, the reviewed literature provides limited empirical evidence on how stocks, buffers, and slack concretely support these processes in practice. After reviewing the articles, one cannot avoid the conclusion that TP research primarily focuses on factors other than enabling learning, which may explain why learning and innovation are often addressed in a superficial and anecdotal manner. In particular, the roles of digital infrastructure and structural and contractual arrangements remain insufficiently explored. For example, it is unclear how digital tools can enhance feedback loops and learning cycles in takt-controlled environments or how contractual models can be designed to support experimentation and shared learning across project stakeholders. These gaps point to the need for more empirically grounded research examining the interaction between production control, organizational arrangements, and learning processes in TP.

From a theoretical perspective, this study contributes to LC research by introducing a system dynamics–informed interpretation of stocks, buffers, and slack as active enablers of learning and innovation. While prior TP research has largely focused on flow optimization and operational control, this study highlights the complementary role of stocks as mechanisms that enable experimentation, innovation, and learning within production systems. This perspective provides a conceptual bridge between system dynamics theory and TP practice, thereby extending the current understanding of learning and innovation in TP.

Finally, what practical methods can be employed to improve learning and innovation in TP? One approach could involve establishing a learning-specific buffer within TP. For example,

instead of empty buffer wagons, this earmarked "experimental wagon" could serve as an innovation platform for teams, with regular working hours allocated for its use. An alternative approach to enabling innovation might involve designating specific locations on the construction site for testing in different ways without halting TP. Model rooms and areas commonly used in construction could be employed in a novel, imaginative manner. A third alternative approach could involve establishing an innovation reserve allocated within the budget for innovative initiatives.

CONCLUSIONS

Prioritizing flow is fundamental to LC from an ideological standpoint, and stocks are often viewed as a wasteful component of the production system. However, system dynamics theory underscores the essential function of stocks in sustaining system equilibrium, whereas an excessive emphasis on flow may result in a constrained viewpoint of the system and potentially unbalanced operational decisions. Having assessed the possibilities of stocks for construction-related learning and innovation in TP systems, this study shifts the perspective from viewing stocks as passive waste to understanding them as active enablers of learning and innovation.

This research emphasizes two primary advantages of evaluating stocks: 1) the sluggishness of stocks facilitates smoother operations and safer experimentation with minimal system disruption and 2) construction, as a dynamic system, maintains stability when the production system is improved, and the advantageous characteristics of stocks are acknowledged. Accordingly, this study proposes a perspective that directs the attention of LC researchers and practitioners from flow toward the beneficial characteristics of stocks, particularly as facilitators of innovation and learning. Overly dualistic perceptions that treat stocks as inherently inferior or merely as waste may result in a system devoid of innovation, which contradicts the core principle of lean philosophy emphasizing learning through lean methods and continuous improvement.

The findings of this study suggest that in TP, stocks, buffers, and slack should not be understood solely as means of managing waste but also as enablers of learning and innovation. In practice, this implies that practitioners should move beyond a purely flow-optimizing mindset and deliberately design buffers to support learning and innovation. This may include allocating time and capacity for experimentation within takt cycles and areas, using buffers not only for disruption management but also for continuous improvement, and distinguishing between waste and productive slack in production planning. As pointed out by this study, practical approaches can be employed to enhance learning and innovation in TP, such as establishing dedicated learning buffer wagons with allocated time for experimentation or designated on-site testing areas.

This study has several limitations, the most notable being its constrained length due to the conference paper format, thereby limiting the discussion of additional pertinent studies connecting system dynamics with TP. The use of citation-based selection (Pareto principle) may have introduced bias toward more established publications, potentially underrepresenting recent research developments in TP. However, this approach was chosen to ensure that the analysis built on a stable and widely recognized body of literature. Consequently, the findings primarily reflect established knowledge, and recent innovations may not be fully captured within the scope of this review. Second, learning and innovation within organizations and industrial systems are not exclusively beneficial, and this study could not examine these adverse effects.

These limitations open several avenues for future research. In particular, empirical studies are needed to examine how different forms of stocks and slack influence learning and innovation in TP systems. Furthermore, the roles of digital infrastructure and structural and

contractual enablers require further investigation, especially in relation to how they may support feedback loops, experimentation, and learning in practice.

REFERENCES

Alhava, O., Rinne, V., Laine, E., & Koskela, L. (2019). Can a takt plan ever survive beyond the first contact with the trades on-site? In *Proceedings of the International Group for Lean Construction.* IGLC27. (pp. 453–464). https://doi.org/10.24928/2019/0261.

Binninger, M., Dlouhy, J., Müller, M., Schattmann, M., & Haghsheno, S. (2018). Short takt time in construction – A practical study. In *Proceedings of the International Group for Lean Construction.* IGLC 26. (pp. 1133–1143). https://doi.org/10.24928/2018/0472.

Chauhan, K., Peltokorpi, A., Seppänen, O., & Berghede, K. (2018). Combining takt planning with prefabrication for industrialized construction. In *Proceedings of the International Group for Lean Construction.* IGLC26. (pp. 848–857). https://doi.org/10.24928/2018/0542.

Dlouhy, J., Binninger, M., & Haghsheno, S. (2019). Buffer management in takt planning – An overview of buffers in takt systems. In *Proceedings of the International Group for Lean Construction.* IGLC27. (pp. 429–440). https://doi.org/10.24928/2019/0226.

Emdanat, S., Linnik, M., & Christian, D. (2016). A framework for integrating takt planning, last planner system and labor tracking. In *Proceedings of the International Group for Lean Construction.* IGLC24. (pp. 53–62).

Fireman, M. C., Saurin, T. A., Formoso, C. T., Koskela, L., & Tommelein, I. D. (2023). Slack in production planning and control: A study in the construction industry. *Construction Management and Economics*, *41*(3), 256–276. https://doi.org/10.1080/01446193.2022.2135749.

Formoso, C., Tommelein, I. D., Saurin, T. A., Koskela, L., Fireman, M., Barth, K., & Disconzi, C. (2021). Slack in construction – Part 1: Core concepts. In *Proceedings of the International Group for Lean Construction.* IGLC29. (pp. 187–196). https://doi.org/10.24928/2021/0183.

Frandson, A., Berghede, K., & Tommelein, I. D. (2013). Takt time planning for construction of exterior cladding. In *Proceedings of the International Group for Lean Construction.* IGLC21. (pp. 527–536).

Frandson, A., Berghede, K., & Tommelein, I. D. (2014). Takt-time planning and the last planner. In *Proceedings of the International Group for Lean Construction.* IGLC22. (pp. 571–580).

Frandson, A. G., Seppänen, O., & Tommelein, I. D. (2015). Comparison between location based management and takt time planning. In *Proceedings of the International Group for Lean Construction.* IGLC23. (pp. 3–12).

Frandson, A. (2019). *Takt time planning as a work structuring method to improve construction work flow* [Doctoral dissertation, University of California, Berkeley].

Halttula, H. P. I., & Seppänen, O. (2022). Situational awareness in construction projects using takt production. In *Proceedings of the International Group for Lean Construction.* IGLC30. (pp. 164–174). https://doi.org/10.24928/2022/0119.

Heinonen, A., & Seppänen, O. (2016). Takt time planning: Lessons for construction industry from a cruise ship cabin refurbishment case study. In *Proceedings of the International Group for Lean Construction.* IGLC24. (pp. 23–32).

Horman, M. J., & Thomas, H. R. (2005). Role of inventory buffers in construction labor performance. *Journal of Construction Engineering and Management*, *131*(7), 834–843. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:7(834).

Kalsaas, B. T., Grindheim, I., & Læknes, N. (2014). Integrated planning vs. last planner system. In *Proceedings of the International Group for Lean Construction.* IGLC22. (pp. 639–650).

Lehtovaara, J., Mustonen, I., Peuronen, P., Seppänen, O., & Peltokorpi, A. (2019). Implementing takt planning and takt control into residential construction. In *Proceedings of*

the International Group for Lean Construction. IGLC27. (pp. 417–428). https://doi.org/10.24928/2019/0118.

Lehtovaara, J., Heinonen, A., Lavikka, R., Ronkainen, M., Kujansuu, P., Ruohomäki, A., & Peltokorpi, A. (2020). Takt maturity model: From individual successes towards systemic change in Finland. In *Proceedings of the International Group for Lean Construction.* IGLC28. (pp. 433–444). https://doi.org/10.24928/2020/0017.

Lehtovaara, J., Seppänen, O., Peltokorpi, A., Kujansuu, P., & Grönvall, M. (2021). How takt production contributes to construction production flow: A theoretical model. *Construction Management and Economics*, *39*(1), 73–95. https://doi.org/10.1080/01446193.2020.1824295.

Lehtovaara, J., Tommelein, I. D., & Seppänen, O. (2022). How a takt plan can fail: Applying failure modes and effects analysis in takt control. In *Proceedings of the International Group for Lean Construction.* IGLC30. (pp. 715–726). https://doi.org/10.24928/2022/0182.

Lehtovaara, J. (2023). *Takt production and decentralized decision-making: Improving construction production flow with novel planning & control approaches* [Doctoral dissertation, Aalto University].

Lerche, J., Enevoldsen, P., & Seppänen, O. (2022). Application of takt and Kanban to modular wind turbine construction. *Journal of Construction Engineering and Management*, *148*(2), 05021015. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002245.

Linnik, M., Berghede, K., & Ballard, G. (2013). An experiment in takt time planning applied to non-repetitive work. In *Proceedings of the International Group for Lean Construction.* IGLC21. (pp. 609–618).

Meadows, D. H. (2008). *Thinking in systems: A primer*. Chelsea Green Publishing.

Moura, R. S. L. M., Monteiro, J. M. F., & Heineck, L. F. M. (2014). Line of balance – Is it a synthesis of lean production principles as applied to site programming of works? In *Proceedings of the International Group for Lean Construction.* IGLC22. (pp. 703–714).

Nightingale, A. (2009). A guide to systematic literature reviews. *Surgery*, *27*(9), 381–384. https://doi.org/10.1016/j.mpsur.2009.07.005.

Proudfoot, K. (2023). Inductive/deductive hybrid thematic analysis in mixed methods research. *Journal of Mixed Methods Research*, *17*(3), 308–326. https://doi.org/10.1177/15586898221126816.

Tetik, M., Peltokorpi, A., Seppänen, O., Viitanen, A., & Lehtovaara, J. (2019). Combining takt production with industrialized logistics in construction. In *Proceedings of the International Group for Lean Construction.* IGLC27. (pp. 299–310). https://doi.org/10.24928/2019/0156.

Tommelein, I. D. (2017). Collaborative takt time planning of non-repetitive work. In *Proceedings of the International Group for Lean Construction.* IGLC25. (pp. 745–752). https://doi.org/10.24928/2017/0271.

Tommelein, I. D. (2020). Takting the parade of trades: Use of capacity buffers to gain workflow reliability. In *Proceedings of the International Group for Lean Construction.* IGLC28. (pp. 421–432). https://doi.org/10.24928/2020/0076.

Tommelein, I. D., Singh, V. V., Coelho, R. V., & Lehtovaara, J. (2022). So many flows! In *Proceedings of the International Group for Lean Construction.* IGLC30. (pp. 878–889). https://doi.org/10.24928/2022/0199.

Tsao, C. C., Draper, J., & Howell, G. A. (2014). An overview, analysis, and facilitation tips for simulations that support and simulate pull planning. In *Proceedings of the International Group for Lean Construction.* IGLC22. (pp. 1483–1494).