

DIGITAL MATERIAL FLOW MANAGEMENT IN TAKT PRODUCTION

Jaakko Riekkilä¹, Olli Seppänen², & Antti Peltokorpi³

ABSTRACT

Efficient construction requires reliable material flow. Modern methods such as takt production increasingly present challenges to the service level of existing material delivery processes. Some specialized contractors, using material management software, already tackle these challenges but there is scant empirical research on their performance and contribution. Therefore, this study investigates such material flow management and aims to reveal insights that could improve them. To achieve this, we first analyzed data from two projects that employed a material flow contractor and utilized a digital material management system. We then interviewed the managers in charge of the material flow systems in the case projects for additional insight. Our analysis indicated that material planning often failed to meet the intended time horizons and to implement a pull signal. The shortcomings stemmed predominantly from organizational inexperience of rigorous material flow management. We also found defects in data quality and management. Deliveries lacked explicit linkage with production, which resulted in batch-size mismatches, so the site team had to often rely on tacit knowledge. The findings suggest that software improvements and training managers in material planning could enhance efficiency. Future research should address especially the barriers to effective material planning and the pull signal implementation.

KEYWORDS

Material flow management, Takt production, data-driven management.

INTRODUCTION & LITERATURE REVIEW

Material flow management is the part of supply chain management that deals with procuring and delivering materials to a construction site as required by the production schedule. Trade partners have traditionally managed their material flows independently, but centralized material management systems have begun to gain traction. Disciplined material flow management can simultaneously reduce supply chain problems and provide a tool for production control and performance assessment. The present study investigates material flow management systems to reveal insights into the systems and to identify improvement opportunities.

A material delivery process that is unreliable or otherwise deficient is one of the leading causes of waste in construction (Dahlberg & Drevland, 2021; Seppänen & Görsch, 2022). In general, these issues stem from the variability induced by the structural complexity and uncertainties inherent in the supply chains. This variability arises from both the demand side and the supply side, as illustrated by Arbulu and Ballard (2004). On the demand side, the

¹ Doctoral Candidate, Department of Civil Engineering, Aalto University, Finland, jaakko.riekki@aalto.fi, orcid.org/0000-0002-0306-2165

² Associate Professor, Department of Civil Engineering, Aalto University, Finland, olli.seppanen@aalto.fi, orcid.org/0000-0002-2008-5924

³ Assistant Professor, Department of Civil Engineering, Aalto University, Finland, antti.peltokorpi@aalto.fi, orcid.org/0000-0002-7939-6612

instability of the production schedule can lead to congestion due to too early material deliveries, unless an effective pull system has been implemented. Likewise on the supply side, unreliability of deliveries even within reasonable lead times can lead to material starvation. Both situations can also cause cascading delays and, at worst, an uncontrollable cycle of replanning leading to further instability. In past research, the delivery reliability side has received more attention compared to how material congestion interferes with production performance (Seppänen & Peltokorpi, 2016).

Fortunately, the variability from the demand side can be mitigated by applying effective production planning and control methods such as takt production. Takt production has indeed enhanced production stability (Lehtovaara et al., 2021), but it has also raised the bar for the service level of material delivery processes (Lehtovaara et al., 2020). This challenge on the supply side requires systematic material planning and management of the information flows that govern the material flows (Tetik et al., 2019). Previous research has proposed models for this purpose (Ala-Risku & Kärkkäinen, 2006; Pinho et al., 2007), but their adoption has remained limited.

Recent takt production projects have integrated external material flow management contractors into their production systems (Riekkilä et al., 2025). The task of these contractors is to assist the trade partners with the material planning and material delivery operations to fulfill the material availability requirements set by the production schedule. A firm grasp of the material deliveries can simultaneously be viewed a tool to control production, because material availability governs which work can be done where (Riekkilä et al., 2024). To manage the planning side of their task, the material managers utilize purpose-built software systems that allow both planning and tracking the material deliveries. The visibility gained through a tracking system could also support situational awareness and performance assessment. Taken together, systematic material flow management shows promise as a toolkit for enhancing construction efficiency, yet research on the topic remains shallow.

The limited research depth likely stems from data scarcity and relative novelty of the topic. Past research has used simulations to bypass the data issue when evaluating the performance of material flow control systems (Tapler, 2014; Zeng et al., 2019). More empirically, Heinonen and Seppänen (2016) detailed a high-maturity case qualitatively but with limited quantitative depth. However, the data footprint of the newly adopted digital material flow management systems could enable deeper empirical quantitative examination. Accordingly, the purpose of this study is to first investigate how the material flow data footprints could allow assessing the functionality and performance of the systems, and second, use that assessment to reveal problems that require future development in current practice. Ultimately, we expect this research to contribute towards unlocking material flow management as a toolkit for production control, situational awareness, and continuous improvement within and across projects.

METHOD

We designed the research as a mixed methods combined exploratory and explanatory sequential study (Creswell & Plano Clark, 2018) that employs case study data gathering and analysis techniques (Yin, 2018). This research design aimed first at a qualitative understanding of the phenomenon so that we could construct a framework suitable for a quantitative analysis. The following quantitative analysis in turn aimed at evidence about the functioning of the material flow system, which then guided a final phase of interviews to supplement the explanation of the phenomenon. The case study data gathering and analysis techniques were appropriate because the target was a complex real-world phenomenon where replication logic could be used for generalization.

We sourced the cases by issuing a call for cases to the Finnish Building 2030 consortium of construction companies led by Aalto University. The case call targeted a wider multiple case

study about takt production control, but from the yielded set of eight cases two contained material flow management systems that were suitable for the present study as a secondary purpose. The call only included takt production projects because we consider it a state-of-the-art production planning and control method that both requires and supports material flow management. Both selected cases were new construction projects that contained an interior takt production phase. Both cases also emphasized material flow management in their preparation phase mainly because they expected the takt phase to require precise just-in-time deliveries to function effectively. Material flow management was important in both cases also because they were located in a city center with little storage space. Both cases tackled the material flow management challenge by employing a dedicated material flow management contractor and by implementing similar material flow management systems with the help of this contractor.

The material flow management systems within the takt phase of each case project was in focus of this research, and the data collection was designed to support it. The main data sources were progress records of production work and timestamps of material delivery units (a set of materials that is moved as a unit, such as a pallet) through the material delivery process. For triangulation of evidence, we also visited the sites and discussed with both production and material flow managers during the production phase. Although the cases shared many features, the takt phases were dissimilar in takt time and nature of the spaces. These dissimilarities along with specifics about the data sources are shown in Table 1.

Table 1: Case descriptions and data sources

	Case 1	Case 2
Description of the takt phase	~20 m2 hotel rooms + corridors, totaling ~5,000 m2, repetitive spaces and balanced workloads	~20–100 m2 office spaces, totaling ~8,600 m2, variable space sizes and workloads
Takt time	2-hour takt time, but mostly controlled daily	1 day
Material flow operator	An external consultant as a full-time material flow manager and a separate contractor for material hauling	One logistics contractor for both material flow management and material hauling
Data sources	Digital material flow management system Takt schedule progress recorded during daily site walks on a mobile spreadsheet application Participant observation, including several site visits and discussions Semi-structured interview with the principal material flow manager Project documentation such as design documents and meeting memos	Digital material flow management system Takt schedule progress recorded during daily huddles on a printed schedule that was later digitized in a spreadsheet 4 site visits, including daily huddles and discussions Semi-structured interview with the principal material flow manager Project documentation such as design documents and meeting memos

The research took the following steps: As the initial exploration phase, we first examined the material flow management systems of the case projects. Based on this examination, we constructed a quantitative analysis framework in the form of a cumulative flow diagram, that represents conceptually an ideal material flow process. The cumulative flow diagram indicates the average progression of material delivery units through the stages of the delivery process, based on the timestamps of passing from one stage to the next. In the second phase, we

processed the takt schedule progress records and material flow datasets from the cases to match the form of the analysis framework. In both cases, the schedule progress records were spreadsheet files, while the material flow datasets were tables exported from relational databases with the same schema. In the material flow database schema, a specific entity for material delivery units contained the process stage timestamps. Merge operations from other tables of the database combined relevant specifics (like material definitions and amounts, delivery destinations, and trade partner names) to these delivery units. The progress records were separate from the material flow database, so establishing a correspondence between the delivery units and scheduled work packages required inference. We explain these inferences in more detail in the findings section. During this data processing, we also made notes of occasionally missing data points that could require interpretation or could be followed up in interviews with the material flow managers. The resulting cumulative flow diagrams of the actual material flow processes revealed several discrepancies relative to the ideal process as well as points of comparison between the two cases. As the final phase, to clarify the discrepancies and points of comparison, we interviewed the material flow managers and used informal site visit discussions of the case projects for deeper insights into the functioning of the material flow management systems.

FINDINGS

ANALYSIS FRAMEWORK

The first objective of this research was to construct a framework for quantitatively analyzing the material flow processes found in the cases. The process in both cases was sequential: material delivery units flowed through defined stages from planning to installation. The datapoints that capture this process were the timestamps at the stage transitions for each delivery unit. The material flow management software (same in both cases) recorded these timestamps as users advanced delivery units through the process stages. Additionally, start–finish timestamps of work packages in the takt schedule complemented the delivery process by assigning to the materials their final status of having been installed. To conceptualize an ideal delivery process, we specified the stage transitions and their target time horizons based on the practices found in the cases (Figure 1). Case 1 documented these stages and time horizon targets explicitly, and, although Case 2 data archives lacked documentation, discussions with its management indicated a similar process. These specified stage definitions and time horizons formed the basis of the analysis framework.

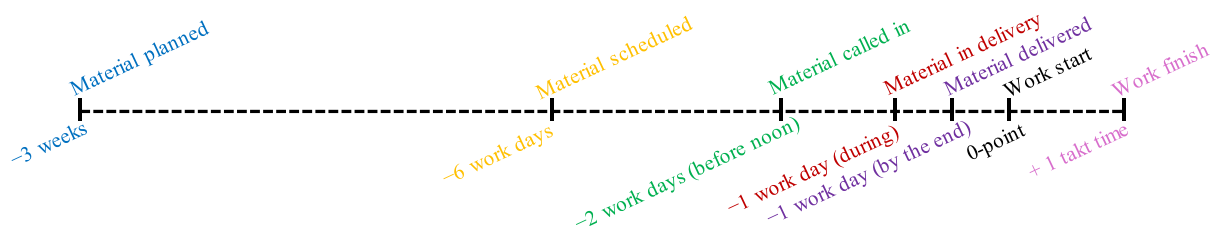


Figure 1: Time horizons for the material delivery process stages (timeline not to scale)

The stage transition timestamps and time horizons found in the cases and illustrated in Figure 1 are described as follows. *Work start* is the anchor point of the process relative to which the time horizons are defined (denoted as the 0-point). The *work finish* at one takt time after the work start is outside the material delivery process, but it can help identify problems and was therefore included in the analysis. *Material delivered* marks a finished delivery to the production location, which should occur by the end of the day before work start. *Material in delivery* is when a supplier has dispatched a delivery from their facility towards the construction site. This should happen during the day before work starts but early enough to leave time for

hauling on site. *Material called in* is a timestamp of delivery verification. The production foreperson must verify each scheduled delivery before noon two days prior to work start. The timing of this call-in request leaves the afternoon of the same day for the supplier to prepare the deliveries of the next day. This is essentially a pull signal from the site and provides the opportunity to postpone or make minor changes to the scheduled deliveries depending on the situation on site. *Material scheduled* is the timepoint when the production foreperson must fix the date and the contents of a planned delivery. Requiring these data six days before work starts provides the supplier five days to pick and pack the materials. This timeframe also allows the site logistics team to plan resources and coordinate non-overlapping deliveries at the gates. *Material planned* represents the minimum three-week planning horizon within which trades must plan upcoming material deliveries. The trades must assign a material delivery unit to each location-specific work package within the three-week time horizon in the takt schedule. Each planned delivery unit must contain the material specifications, rough quantities, and an estimated delivery week. These stages and timeframes were designed to secure reliable material availability and to ensure all stakeholders have sufficient time to prevent congestion during receiving and hauling materials.

A cumulative flow diagram is an appropriate framework for analyzing a sequential process. An example of the form of an ideal material flow process is presented in Figure 2. The lines in Figure 2 represent the cumulative proportions of delivery units (relative to the total amount of delivery units; y-axis) that have been timestamped to the corresponding stage at each point in time (x-axis). Three analytical insights can be drawn from the figure: 1) the vertical distances between the lines signify the proportion of delivery units that are in the last timestamped stage, 2) the horizontal distances indicate the durations that delivery units should spend in the last timestamped stage based on the time horizons, 3) the relative slopes of the stage transition and work package lines represent balance of the material flow process (equal slopes signify perfect balance). The x-axis scale in Figure 2 is artificial (adjusted to visualize the concept) and therefore so is the absolute value of the slope of the lines. The two dotted lines represent the start and finish of the work package in the takt schedule. This conceptual framework supports the interpretation of the case data by providing a comparative reference point of an idealized process.

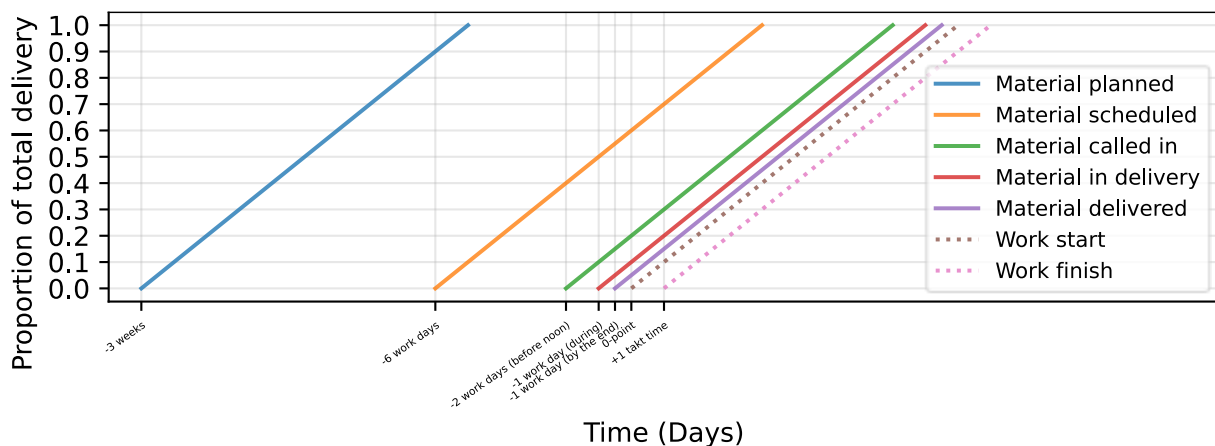


Figure 2: A conceptual framework for analyzing a material flow process.

We can assess the performance of material flow management by comparing the cumulative flow diagrams constructed from case timestamp data to the framework. Data from a high-performing case should align with the structure and patterns of the analysis framework. For example, we can measure the durations of stages as horizontal distances between the lines and compare them to the planned time horizons. We could also assess the stability of the process by quantifying the deviation of slopes of the stage lines from the planned work start line. As a

specific example, we can compare the average time difference between finished deliveries and work starts against the expected value of less than one day, and crossings of the lines would signal late deliveries. As a caveat, the validity of these comparisons relies on sufficiently high-quality and complete data, which may not hold. In addition, first-time implementation and the absence of contractual enforcement of the timeframes in the cases led us to expect imperfect alignment with the ideal process. As a practice-based contribution, the framework warrants further empirical and academic scrutiny, yet it is adequate for the purposes of the present study.

CASE DATA PROCESSING AND RESULTS

Constructing the cumulative flow diagrams for the cases required data processing. This need arose from two issues: the datasets originated from two separate systems and all sources contained missing values and errors. We next detail the processing steps used to address these issues and present the resulting cumulative flow diagrams.

The first issue was the absence of an explicit link between work package progress records and material delivery units. Although the documented material flow process in both cases required each delivery unit to be assigned to a work package, no such assignments existed. The material management database included fields for work phase, trade, delivery location, and contained materials. Of these, the work phase field was intended to capture the work package assignment. In practice, entries to this field were generic and did not map to the takt schedule work packages, adding nothing to the other fields. This gap likely reflected reliance on tacit knowledge by the material-flow manager and trade forepersons who used the system. To address this, we inferred the assignments by matching the trade and material contents of each delivery unit to the corresponding work packages. For example, we assigned units belonging to the drywall trade containing drywall materials to drywall work packages. These inferences proved reliable but were labor-intensive and depended on detailed tacit knowledge of work contents and required materials. Future projects should record explicit links between delivery units and work packages to enable scalable analysis of material flow data.

The second issue concerned missing and erroneous data that required cleaning. Both cases included work packages that were never recorded as finished and delivery units that lacked one or more timestamps. Some material deliveries were not recorded in the system at all because small items were delivered outside the system. Delivery locations were not always specified at the takt area level because different materials followed different delivery strategies. In such cases, we assumed a single delivery unit corresponded to all work packages within the broader location. The intended one-to-one relationship between the material delivery units and work packages did not hold either. Some work packages were linked to more than one delivery unit, while some delivery units covered several adjacent work packages when they belonged to the same trade. These anomalies reduced data validity to a degree, but they did not compromise the objectives of the study. The analysis framework does not depend on a strict one-to-one mapping between work packages and delivery units. Moreover, several work packages contained sufficiently complete data for analysis. Out of these work packages we selected the drywalls as the unit of analysis for this paper.

The cumulative flow diagram for the drywalls in Case 1 in Figure 3 reveals substantial deviations from the benchmark in Figure 2. First, the intended three-week planning horizon is effectively absent (the blue and orange lines are mostly obscured by the green line). Second, the time difference between the scheduled and called in timestamps was nearly zero with only a few exceptions. This pattern indicates that the material management process skipped the planning and scheduling stages and began at the called in stage. As a result, the horizontal distance between the called in and in delivery lines represents the material planning duration. This distance ranged from 0 to 6.8 days, with an average of 2.2 days, even though the intended duration was one day. This again suggests that the called in stage functioned as the entire

planning horizon rather than as a pull signal. Yet, from the production perspective, suppliers appear to have dispatched materials consistently ahead of production. The in delivery timestamps were on average 5.1 (ranging from 0 to 16.4) days ahead of planned work start. Only around day 15 do the in delivery and work planned start timestamps converge to a distance of less than one day, the shortest value being 0.6 days. Finally, the delivered line crossed the work started line at points 1 and 2, which would normally indicate material starvation. However, the data pattern suggests that delivered status records were occasionally inaccurate and updated in large batches. Overall, Figure 3 indicates that the material process largely operated ad hoc rather than within the intended time horizons. On the one hand, deliveries seem to have been mostly on time, but on the other hand, they were mostly too early compared to the ideal process.

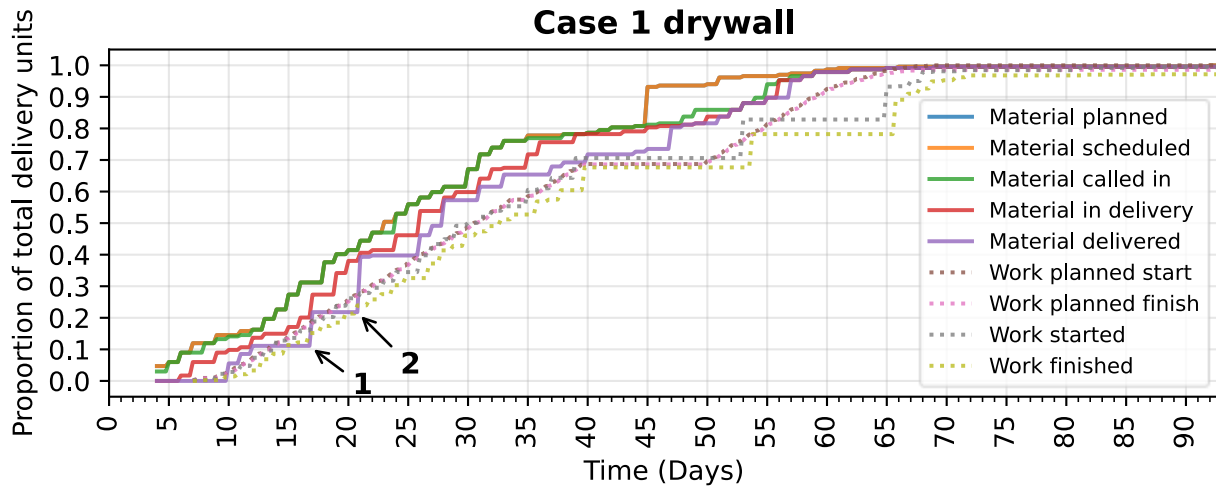


Figure 3: Cumulative flow diagram of delivery units for the drywall work packages through the stages of the material delivery process in case 1

The story of the drywalls in Case 2 in Figure 4 is broadly similar to Case 1. As in Case 1, the gap between the planned and scheduled timestamps is effectively absent. Unlike Case 1, the scheduled timestamps were often recorded in large batches (vertical jumps in the orange line), placing them several weeks ahead of the called in events. This pattern suggests the process bypassed the planned stage and used the scheduled stage to serve its purpose. The batching implies an uneven planning process with sprints followed by idle periods. The subsequent called in timestamps follow a relatively smooth curve, interrupted only around days 34 and 66. The gap between the called in and in delivery stages was on average 3.6 days, ranging from 0 (resulting from a recording error) to 14 days. As in Case 1, this variability indicates that the called in stage did not function reliably as the intended pull signal. Considering this, we can consider the gap between the scheduled and in delivery timestamps as the total planning horizon in Case 2. This gap was on average 9.8 days, ranging from 0 (a recording error) to 24.9 days. The in delivery and delivered stages also mirrored Case 1, with materials typically arriving more than one day before the planned work start. The average gap between the stages was 2.6 days, ranging from 0 (a recording error) to 8.2 days. The delivered timestamps exhibit late batch recording similar to Case 1, as at points 1–3 where the delivered line crosses the work started line. Occasional vertical jumps in the in delivery line, such as at point 4, likely also reflect delayed data entry rather than actual delivery events. Discounting these recording anomalies, material availability for production appears to have been high, as in Case 1, evidenced by the fact that materials were mostly recorded as delivered ahead of work start. However, this availability likely came at the cost of on-site material buffers created by earlier than required deliveries. Table 2 summarizes the main findings of the cases. The findings are organized around four general aspects for comparison.

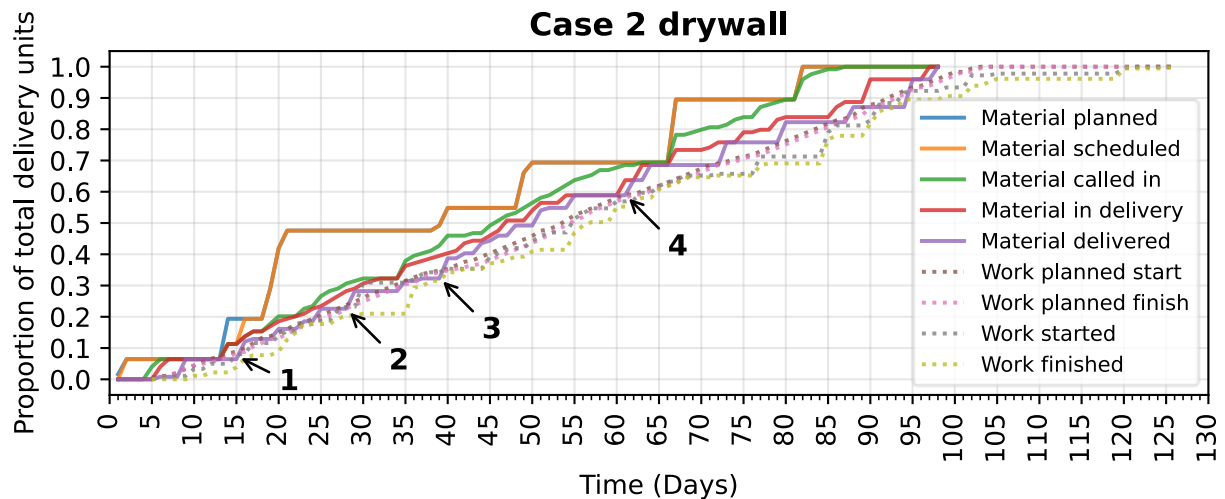


Figure 4: Cumulative flow diagram of delivery units for the drywall work packages through the stages of the material delivery process in Case 2

Table 2: Summary and comparison of findings based on the case data

Aspect	Case 1	Case 2	General
Material planning	Backed up by the called in stage only, leaving an average 2.2-day (ranging between 0–6.8 days) planning horizon	Covered by periodic sprints at the scheduled stage, leaving an average 9.8-day (ranging between 0–24.9 days) planning horizon	Planned stage was not used, intended time horizons were not achieved
Pull signal	Call in requests used more likely as the planning stage	Call in requests mostly several days ahead of production start	Call in request was not used as a pull signal, but instead as a substitute for scheduling deliveries
Material availability and on-site buffers	Deliveries mostly 1–5 days ahead of production	Deliveries mostly 1–5 days ahead of production	Material availability was mostly secured with on-site buffers worth 1–5 days
Data quality	Occasional batching of delivered timestamps Location assignments not takt area specific	Occasional batching of in delivery and delivered timestamps	No explicit link between delivery unit and work package

INTERVIEW RESULTS

The post-analysis interviews with material managers deepened these findings. The analysis results suggest that the intended material planning process was hardly followed and the material managers corroborated this result. They expressed some frustration at this issue and emphasized that better planning would improve the performance of the material flow process. One suggestion was that while BIM-based information take-offs already benefit the material planning process, more specific product and quantity information could enhance this benefit.

The pull signal was also deficient. The interviewees cited that teams in both cases used daily site walks to gauge production status, and they postponed some deliveries when progress lagged, but these decisions did not flow through the call in requests of the system. The explanation for

this was largely software usability issues, but a lack of training and enforcement of the process were also probable contributors. Situational awareness remained largely tacit and was transferred mostly through daily huddles, instant messaging, and, in Case 2, a parallel cloud spreadsheet system. The interviewees also mentioned communication as one of the biggest problems for controlling the material flows. It therefore seems that the adopted process and software failed to fulfil one of their key purposes, that is, improving information flows.

Overall, from a material availability standpoint, according to the interviewees, the process performed well in Case 2 and moderately in Case 1. However, the interviews reinforced the results suggested in Figures 3 and 4 that on-site buffers due to too early deliveries did cause intermittent congestion in both cases. Further supported by case discussions and observations, we found that trades tend to prefer a surplus of materials on site over the risk of shortages.

The material flow managers were primarily responsible for data entry, which underscores their central role in producing usable records. In principle, suppliers should have recorded the in delivery timestamps and site hauling teams should have recorded the delivered timestamps. In practice, as interviews confirmed, these users sometimes failed to enter data, and the material flow manager backfilled missing points using after-the-fact tacit knowledge.

Another data management issue stemmed from the separation of digital systems. The material managers and trade forepersons endured with tacit knowledge of the linkages between schedule and materials and saw little value in entering the work package assignments explicitly. The lack of integration enabled bypassing the intended one-to-one relationship between the delivery units and work packages. The interviewees partly viewed this improvisation as beneficial for flexibility, yet it arose from limited process maturity rather than deliberate design.

Related to these data issues, both interviewees described the material management software as slow and cumbersome to use. Consequently, the Case 2 logistics team used a parallel cloud spreadsheet to track upcoming and completed deliveries. They found the spreadsheet easier to use and entered the same data into the material system only afterward. Although Case 1 stayed within a single system, the manager also reported usability frustrations rather than strong endorsement.

DISCUSSION

The observations about wanting material planning echo the rationale of Ballard (2000) for lookahead scheduling and the make ready process in the Last Planner® system, whose goal is to secure prerequisites such as materials for upcoming tasks. In a takt production context, once upcoming work has been planned in detail, teams should be able to plan materials well ahead of production. A finer grained view and increased visibility into the material demand should contribute to waste reduction through earlier identification and removal of constraints. We found no compelling explanation for the weak emphasis on planning beyond limited organizational maturity. These findings point to the need for more systematic training and coaching in material planning. More mature general contractors could help less mature trade partners by providing training and by specifying required planning horizons in contracts. The realized planning horizon during a project could serve as a leading indicator of future production performance.

Material planning is also an integral part of broader product information management, as discussed by Peltokorpi and Seppänen (2022). While design specifies what materials the production process installs, production ultimately determines the actual material demand of the project. These processes can support each other with systematic information exchange. In return for BIM-based structured material data from the design process, systematic material planning can supply verified demand and timing data back to the product information management system.

Arbulu et al. (2003) challenged construction companies to adapt a kanban strategy to pull materials to the site. Beyond largely skipping the planning stages, the cases in this study also failed to use the call in requests as the intended pull signal. Improved planning discipline and a functioning pull signal could help to curb the tendency of trade partners to hoard materials on site. The freed-up space could in turn cut waste through reduced risk of congestion and therefore support production flow. Our findings suggest that organizations should invest more in training and coaching to make the kanban strategy work as intended.

One objective of the study was to assess the quality of data captured by digital material flow management systems. In principle, the data footprint of the delivery process should support production control, situational awareness, and continuous improvement. In practice, the datasets contained clear timestamps that could reconstruct actual material flows, even though the software was used in ways that diverged from the intended process. A practical lesson was that the systems hardly provided useful metrics during production in the cases.

The framework in Figure 2 presents a method for a quantitative assessment of the material delivery process based on the timestamp data. For example, the stability of the material delivery process could be measured by the variance of the stage lines relative to the material demand set by the schedule. As another example, the durations of each stage could be calculated for every material delivery unit. These measures could be converted into performance metrics to set targets and track progress in continuous improvement within and across projects.

Beyond not following the defined process, the data were not perfect for three main reasons. First, users other than the material managers had limited incentives and sense of purpose for entering data as intended in the process, which resulted in after-the-fact late record batches highlighted in Figures 3 and 4. Second, the delivery units and takt work packages had no explicit linkage, which stemmed from the separation of the scheduling and material management systems. Third, users often found the material management software slow and cumbersome to use, which led to adopting parallel communication channels. On the one hand, overcoming these issues by relying on improvisation and tacit knowledge allowed the system to run reasonably well. On the other hand, better planning through training and organizational development, integrating the systems, and improving the software would likely provide a more scalable route to reliable flow.

CONCLUSIONS

This research investigated digitally supported material flow management systems in takt production with a mixed methods case study approach. We found that the data footprint of a material flow management software allows assessing the performance of the material planning and delivery process and the availability of materials on site. We showed that this assessment ability can support production control and continuous improvement by providing situational awareness and quantitative performance metrics of the material flows. The findings however also indicated that the intended material planning and delivery process often failed, stemming from lack organizational maturity and deficient software tools.

Although this study was limited to two Finnish takt production cases, suffered from data quality issues, and analysed a single work package, the patterns observed are likely indicative of similar issues in other contexts. Future research should identify and characterize barriers to effective material planning. Another priority is to design and test more robust methods for implementing a reliable pull signal. The framework in Figure 2 and the proposed performance measures also merit further scrutiny and refinement. For example, its practice-based stages and time horizons could be adapted to different material types, degrees of supplier integration and flow characteristics. Furthermore, adopting automation technologies to replace manual data entry could improve data quality and reliability. The central practical implication is to prioritize material planning as the starting point for stabilizing material flows to support production.

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