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RIGOROUS 2-HOUR TAKT REVEALS UPSTREAM UNDERPERFORMANCE

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ABSTRACT

The primary purpose of this study is to demonstrate that rigorous production control requires high quality and flawlessness in the upstream production process. The research approach is a quantitative case study. One-piece flow forms the theoretical framework combined with the "sea of inventories" logic. The empirical material is collected from the case company's renovation projects' data, documentation, meeting minutes, and training material.

The definition, modelling, and analysis of the production system are fundamental to continuous improvement in construction. Systematic analysis, documentation, quality control, and quality assurance enable fact-based improvement and control of the production system. Our study, following the logic of continuously tightening requirements for control variables in the production flow, reveals upstream underperformance and drives the elimination of the problems, thus improving efficiency. In our case, company evidence shortening the takt from 4 hours to 2 hours reveals hidden problems in upstream flow, resulting in continuous improvement in production quality. Overall, our study provides evidence of the applicability of one-piece flow in construction.

KEYWORDS

One-piece flow, Toyota Production System, JIT, Takt

INTRODUCTION

The construction industry has used the Toyota Production System (TPS) and Lean methods since the 1990s. Still, results in increased productivity have not been rooted in the industry despite numerous successful Lean interventions (Pekuri et al., 2011; Da Rocha et al., 2022). Lately, Riekki et al. (2023) suggested that takt production could work as a ground-up driver towards implementing a Lean-based production system for construction.

Research has shifted to takt production and flow to increase the construction industry's productivity. At least four schools of thought can be distinguished from takt production: Takt Time Planning (e.g., Tommelein and Emdanat, 2022), Takt Planning and Takt Control (TPTC) (e.g., Binniger et al., 2017), Takt Time Planning (Gardarsson et al. 2019) and "hourly takt", takt production based on one-piece flow (e.g., Riekki et al., 2023). Research has tried hard to define the construction physics (Bertelsen et al., 2007) and flow of construction (Sacks 2016). Still, it has ended up where so many things flow that there is no unambiguous name or definition for

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all identified flows (Tommelein et al., 2022), or the flow is just not flowing in the construction industry (Rocha et al., 2022).

In addition to the inability to formulate a theory for a holistic approach to a lean construction production system (Riekki et al., 2023), the research in the construction industry has not recognised products (different types of buildings), upstream processes or their importance as part of the production system. In contrast to TPS in the automotive industry, product development plays a minor role in the construction industry (Pekuri et al., 2014). Instead, construction companies typically outsource product development to subcontractors without realising that the construction and the assembly phases are some of the most critical stakeholders in setting the product requirements for industrial manufacturing (Stevenson, 2021, p. 165; Hopp and Spearman, 2011, p. 4; Fujimoto, 1999, pp 112-113). Without systematic product development, there is no systematic production capability creation, which would result in systematic production development (Annunen and Haapasalo, 2022; Annunen and Haapasalo, 2023). This underlines the observation that craftsman production (Womack et al., 2007, pp.19-24) is the predominant product design and production form in the current construction industry ("prototype production"). The focus of productivity development in the construction industry should be to transfer the design and construction from artisanal production first to the beginning of the industrial era. Then, we can take it further step-by-step and not, as is currently the case, transfer the characteristics of highly developed production methods in companies to a system based on craft production.

Based on the above, this article examines the basis of a construction production system and the enhancement of the production system in a case company, which brings previously hidden problems to the fore and their root causes. Thus, the main goal of this article is to show that rigorous control of production requires flawlessness of the upstream production process and thus causes a continuous improvement in the production quality as the more stringent control is moved. This goal is pursued through the following research questions:

1. RQ1: How is the one-piece flow used in the 2-hour takt case project to reveal the problems of the production system when compared to the previous 4-hour takt project?
2. RQ2: What are the problems and the root causes in upstream flow revealed by shortening the takt (4h takt to 2h takt)?

In this paper, we first review the literature to understand the relation between one-piece flow and eliminating disruptions (poor design, procurement, prefabrication, logistics, quality), resulting in quality and productivity improvement. Second, we describe our case study production system and analyse how the change from 4-hour takt to 2-hour takt has revealed more detailed failures. Also, we identify their respective failure mechanisms in the upstream process, leading to improved performance in the production system. We deliver case evidence on the applicability of one-piece flow in construction when carefully applied.

LITERATURE REVIEW

ONE-PIECE FLOW

The just-in-time (JIT) concept is part of TPS which creates a pull flow to the production, which forces the previous part of the process to do what the next part of the process (customer) needs. Part of the JIT is one-peace flow which brings the problems to the surface if implemented meticulously. The benefits of one-piece flow are undeniable: it builds in quality, creates natural flexibility due to shortening lead times and creates higher productivity since it reduces the cost of inventory and unleashes people's creativity. Simultaneously, it improves safety and morale (Liker, 2020, 71-73). If a problem surfaces, the entire production line is forced to shut down. This, in turn, forces everyone to stop and fix the problem so production can continue. This way, the crew and the process evolve. The one-piece flow with a short lead time enables higher quality because there is no large buffer of faulty parts when the defect surfaces. Also, part of the one-piece flow is that the next part of the process acts as an inspector for the previous part, and the defects are quickly found (Liker, 2020, pp. 61-76).

SHOP FLOOR CONTROL AND PRODUCTION SYSTEM

Hopp and Spearman (2011, p. 481) define Shop Floor Control (SPF) as the point where production planning interfaces with processes. They suggest that production control works best under stable conditions, which is precisely what TPS aims for. Unfortunately, creating such an environment can conflict with business requirements. As a result, in industrial production, part of the production is carried out in production systems, where some of the methods highlighted in Toyota's TPS research either do not fit well or do not fit at all (Irani, p. 36, Table 2.2). When classifying production systems and assessing their usability, one must understand the product being produced, its volume, and its variation—i.e., how many articles of the same product are intended to be manufactured. This product volume (Low vs High Volume) – product variation (Low vs High Mix) forms a product-process matrix. A low-volume, high-variation (LVHM) product can be considered more demanding to manufacture than a product with high volume and low variation (HVLM). Therefore, every Toyota facility is engaged in improving with Lean the productivity of HVLM assembly lines, which are very inflexible production systems (Irani, 2020, pp. 26-34; Chryssolouris, 2006, pp. 332-334; Hopp and Spearman, 2011, pp. 6-11).

The Bill of Materials is an essential part of the information maintained and processed by Manufacturing Resource Planning (MRP) for managing material flows in industrial production (Hopp and Spearman, 2008, pp.116-119). During the design phase, the designed parts, materials, subassemblies, and other objects combined with their part hierarchy can produce the Engineering Bill of Materials (E-BOM). Actual manufacturing requires the Bill of Materials at the purchasable part number (Manufacturing BOM or M-BOM) level and the corresponding article hierarchy (Sheng-Hung et al., 1997, Stevenson pp. 562-564).

The smaller the batch size, the more flexible the production system must be. As Lean focuses on cost reduction through waste elimination, the Theory of Constraints (TOC) provides a competing manufacturing strategy (Irani, 2020, p. 25) as its goal is to maximise flow through the entire system by identifying bottlenecks, balancing the flow and eliminating constraints (Stevenson, 2021, p. 715). Yet another production strategy is controlling the production system via Work in Progress (WIP). A pull system can be implemented with Kanban, but it is far easier to limit the amount of WIP to a constant level and use a Constant WIP (CONWIP) production system for pull production (Hopp and Spearman, 2011, pp. 363-368). All these strategies can be used for implementing a production system, and the question arises of which would be compatible with construction.

RESEARCH APPROACH AND LOGIC OF THE PAPER

Our research follows a case study approach, defined by Yin (2009), aiming to utilise the research material of one company. The target company of the case study was chosen because it has been developing production efficiency in two business units simultaneously using the same method, i.e., one-piece flow. The study chose between two business units and their different applications of one-piece flow based on the management and maturity of the manufacturing process. In the project selected for the study, 1) the manufacturing process was more comprehensive and 2) described in greater detail at the task level for workers. Also, the manufacturing process 3) utilised more prefabricated components and 4) employed a documented and trained management system for daily and weekly management. In other words, the selection criteria for the study were the extent of systemic change in product, design, procurement methods, contract models, the extent of one-piece flow usage, management of the manufacturing process, and team management. The research team also considered the significance of the takt duration for the study. It concluded that a 2-hour takt (implemented three times a day, leaving 2 hours as a daily buffer) is more significant than a 4-hour takt, where, based on observations, the wagons had more built-in buffer than in the selected project.

This research also shows how the one-piece flow principle of the TPS applies in the construction process, where effort is put into controlling variation in the production. This, in turn, has required and will require significant improvement in the quality of the upstream process in the studied business unit. Here, we apply the logic from the "sea of inventories" to more rigorous time control of the system. The empirical part is two-phased, based on first the description of the case project and details of the 2-hour takt. The quantitative study focuses on which deviations emerge after moving from a 4-hour to a 2-hour takt. The system's capacity can be utilised comprehensively only by analysing and eliminating the causes of disruptions, and therefore, design, procurement, design for the prefabricated parts and elements, off-site prefabrication, delivery, site-logistics and the construction process itself are studied as a production system.

The focus of the empirical analysis has been the implementation of our case company's refurbishment process of bathrooms. The model of the 2-hour production system was created together with the production team as they prepared for their next project, and the documents and organisational instructions were used as a reference. Our data was collected from the backlog of the previous 4-hour and 2-hour projects (contracts, planned and performed schedule), financial final accounts and deviation accounting maintained during the implementation phase of the projects, as well as defect/deficiency lists made in the projects and approvals of implemented repairs from the quality management system. The research team also accessed the project organisation's schedule analysis after the 2-hour project concluded. The most critical part of the study was the event data on deviations produced by the day-to-day management model of the last two projects, which the research team used as the starting point for quantitative analysis. This event data was classified and supplemented using WhatsApp records and analyses produced by three lean interventions on the implementation problems of one-piece flow. As a result, a comparison of the deviations in the 4-hour and 2-hour production systems was obtained and categorised data from the 2-hour project was integrated into the production system model. Using this framework, the aim was to formulate improvement suggestions to utilise one-piece flow and reduce production variability more effectively.

DEVELOPMENT AND DESCRIPTION OF THE PRODUCTION SYSTEM – CASE STUDY

The researched business unit primarily renovates residential buildings constructed in the 1960s and 1970s using a concrete element frame system. These renovations typically involve replacing water, sewage (occasionally also heating), and electrical systems, necessitating the dismantling of bathrooms and toilets down to the concrete framework in the apartments. Also, projects include the dismantling and renewing of the corresponding systems in the basement and the required connections to the municipal water, sewer and heating systems at the plot. Therefore, renovations vary depending on the surrounding city infrastructure, the size of the residential complex (number and type/size of buildings), and the geological conditions of the site. The organisation aims to achieve a lasting competitive advantage in the HVLM market by industrialising its production system and portfolio-based business model as described in Portfolio/Process/Operations-model (PPO, Korb et al. 2017, pp.165-167).

From Theory of Constraints (ToC) to Takt Production

The pipeline renovation business unit encompasses two distinct business models based on one-piece flow and subcontracted work. The studied organisation has systematically developed its production system to manage manufacturing. The organisation initiated the transformation from the traditional subcontracting method to partnering. Initially, the projects were subdivided, and subdivisions were tendered, repeatedly purchasing them as cheaply as possible from ever-changing subcontractors (black-box tendering) using the customer's design for HVAC.

The first step of the business unit towards developing an industrial production system was establishing a production Alliance. This objective was to standardise the production method by maintaining a consistent team and striving for longer-term collaboration with trades, employing the Alliance project delivery method starting in 2015 (Korb et al. 2017). However, the recurring problem on sites was the persistent variation, which led to applying ToC to identify and address workflow bottlenecks. Nonetheless, poorly designed details make the renovation process susceptible to variation. In the Design-Bid-Build (DBB) project delivery method, which the clients widely use in the Finnish bathroom refurbishment market, the main contractor is not adding value to HVAC designs. Instead, the main contractor uses the exact customer-originated 2D drawings in tendering for separate trades. As a result, the subcontractors are responsible for creating the implementation design and selecting the parts and materials, often while the work progresses. The Alliance method proved to be ineffective in solving various production-related problems. The project manager summarised that the production bottlenecks shifted faster than they could be identified and controlled. In 2019, the team moved to use the CONWIP model to gain control over the design and production processes to standardise products and work in some form. At the same time, the organisation transitioned to a partnership model with selected subcontractors, conducting business together based on the open-book principle.

The use of CONWIP as a core of the production system shifted the responsibility for completing plans, products, and materials, as well as understanding the execution of work, to the main contractor's organisation. Gradually, the organisation's ability to create and manage the housing manufacturing process as a whole grew to an exceptional level for a leading contractor in the market. Moving from a zero-sum game business to partnering enabled the transition to takt production, initially implemented with 4-hour takt and takt logistics. Project by project, the organisation improved its manufacturing planning expertise towards an LD400 level in each wagon. This led to more precise parts lists (M-BOMs) for procurement and logistics while simultaneously refining the standard product and standard work (manufacturing process). Continuous ambition to refine design towards the LoD400 level, increased design precision to form M-BOMs for each wagon, and the ensuing opportunity to meticulously plan and execute the production process down to the minute raised the maturity of the production system to its current level. During the last three projects, the organisation has systematically transferred material processing and assembly to a separate production facility, a "factory", causing the prefabrication level to increase drastically.

The continuously improved takt production system aims to execute construction using a one-piece flow. Because the renovation projects vary across the market area, each project is divided into two parts: the process and the project part. The process uses takt production, and its design is refined to LoD400. The project part is executed using a traditional management model influenced by the LPS. From the manufacturing industry production systems perspective, the unit has separated the recurring renovation of similar residences into a one-piece flow based on product and process standardisation, referred to as the HVLM production system. Over six years, the production system has been developed to increase production flow from 150 apartments in 2018 to 330 apartments. Meanwhile, the organisation and direct costs have grown by approximately 15% during the same period.

THE PRODUCTION SYSTEM IN THE CASE PROJECT

The core of the production system is the manufacturing process and its management. The organisation believes managing the manufacturing process necessitates control over the products (apartments) and their production. Consequently, the organisation of the business unit focuses on two principal tasks: 1) product design and 2) manufacturing planning. Since changes in the product invariably affect manufacturing, and alterations in manufacturing methods impact the product, the studied organisation has formed a single, cohesive and interactive team to implement their production system without hierarchical or organisational boundaries. The objective of designing the production system is the capability to plan all necessary materials and then required tasks from the beginning of manufacturing (a bathroom dismantled to concrete) to the finished product (a zero-defect delivered apartment). The studied organisation has set itself the goal of transitioning to industrial production, where the organisation is responsible for the product, all its materials, parts, tasks, work techniques, tools and procedures from design to installation. The responsibility also includes transitioning to hourly work, using the employer's unilateral right of supervision, and superseding subcontracting.

The project was implemented using the DBB method, where the client commissioned what is incorrectly known in the market as a feasible 2D design. The business unit had won the tender based on price. During contract negotiations, the implementation organisation developed the design so that the project could use as many established solutions and materials as possible that are known to be compatible with a one-piece flow production. Hence, the production system consisted of three segments: A) product/manufacturing process design and procurement, B) apartment manufacturing process and C) off-site prefabrication and supply chains. The production system is depicted in Figure 1. The design was an iterative process, and it consisted of the following subprocesses: 1) product design, i.e. apartment HVAC design; 2) pre-fabrication design; and 3) manufacturing process planning: creating M-BOM per apartment type, work breakdown structuring and formulating task lists per apartment type and staging and levelling the wagons. Since the design created and maintained M-BOMs, it also controlled the 4) procurement and takt logistics. The apartment manufacturing process was separated from the project on-site management, and the 5) daily operations and management included daily huddles for team members (TMs) and team leader (TL). The group leader (GL) met daily with TLs following the standard management procedure and problem-solving process. These meetings were also attended by design, prefabrication, procurement and project management. TLs and GL managed 6) logistics on-site and took care of 7) call-offs for JiT deliveries for both prefabricates and materials.

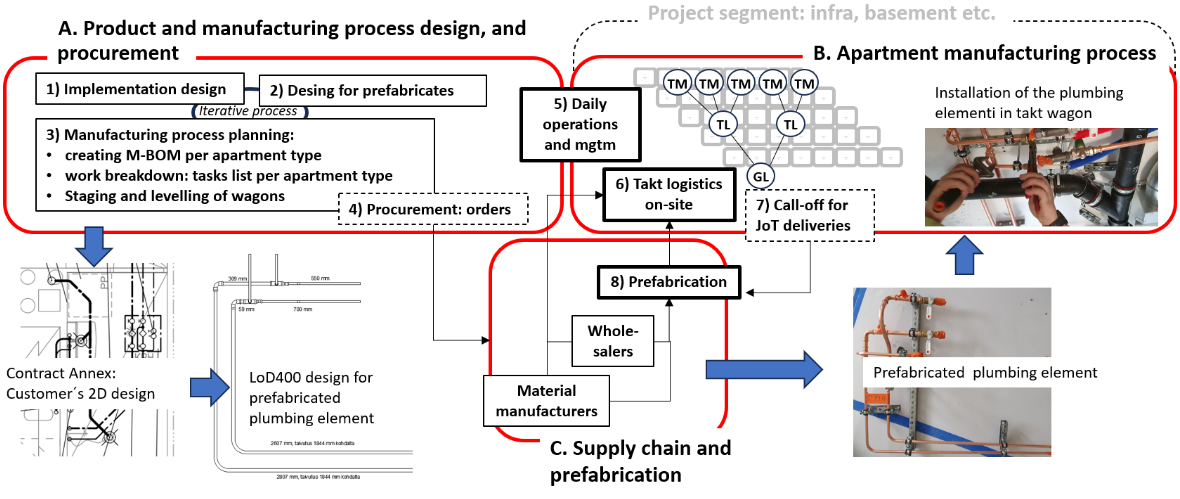

Figure 1: The modelled production system, which uses one-piece flow as a core

Timewise, the project was divided into two main phases: the production preparation phase and the production phase. The production preparation phase focused on prefabrication design, material selections, procurement planning and JiT-logistics. The prefabrications were designed to be millimetre precise for manufacturing, and simultaneously, M-BOM was formed for each apartment. Depending on the apartment type, the number of items in the M-BOM varied between 280 and 300 separate articles. The prefabrications reduced the number of parts and material items delivered to and built on-site by about 50-70 items per apartment. The apartment-specific parts and prefabrication list were the basis for planning takt-logistics, scheduling, and placing orders. It was also used to update the manufacturing process task list, which the organisation aims to shorten and specify with each project. There were 246 defined tasks in the studied project, for which duration estimates at the minute level and worker competency requirements were empirically defined. Using the task list created with the help of the plans and the M-BOM, a 2-hour takt train was formed, in which tasks were distributed and levelled across the wagons based on estimated task durations. The design principle was to leave a 15 – 30-minute buffer depending on the expected variation in each wagon and the daily 2-hour buffer. In levelling, the aim was to manage and balance execution time at a minute level, concentrate on specific tasks according to competency requirements, and consider staff capabilities. For prefabrications, the decision criterion in product design was the smoothness of the 2-hour takt and the reduction of throughput time. The manufacturing time of prefabricated components was not considered in the decision-making process, as there was insufficient data on actual manufacturing times.

The formation of the takt train created the prerequisites for resource allocation and the formation of teams for implementation. The structure and organisation of the production system were arranged by dividing the manufacturing process (adjacent wagons) into three teams: demolition and installation of vertical HVAC lines (wagons 1-3), casting, installation of horizontal HVAC lines, and tiling (4-11), and installation of fixed furnishings and finishing works (12-21). In each team, a team leader was responsible for team members implementing their wagons, daily supervision of workers, problem-solving and escalation, and work safety.

RESULTS AND DISCUSSION

The two-layer daily management model, which was adopted from TPS, was designed based on experiences from the 4-hour takt to control the manufacturing process and resolve problems arising in manufacturing. Based on interviews with management, the goal was for the team members of the three teams to be at the top of the hierarchy. Other levels of the organisation, team leaders, group leader, planning, procurement, and prefabrication, were supposed to support the team members, the actual operators implementing the manufacturing process. The project shifted to a 2-hour takt, similar to previous projects that used a 4-hour takt, prefabricates, standardised parts and materials, and established daily management practices. The team members were mainly the same as in the 4-hour takt, but the task contents were changed while the degree of prefabrication was increased. The product was expected to become more straightforward regarding prefabricated components, which resulted in a shortening of the manufacturing process and throughput time. In numbers, the shift from a 4-hour takt to a 2-hour takt changed the execution so that instead of the previous 40 units in a 4-hour wagon, the manufacturing process aimed to be implemented in 37 units of 2-hour wagons, of which 15 units had one or more prefabricates. Consequently, the throughput time for an apartment was reduced from 160 hours to 74 hours. Each day included an empty wagon as a buffer, so the calendar time for apartment throughput was decreased from 20 weekdays to 12,4 weekdays. The hours spent on factory work were not tracked for the prefabrication part, except for individual trial installations, which showed a time saving of 30-70%.

The project personnel conducted a more detailed internal evaluation based on the actual takt schedule for the part of the project they deemed most important (the C and D staircases, with 24 apartments, which they considered too large batch size after analysis). According to this assessment, there were start delays of 2 working days and completion delays of 5 working days, which meant that the throughput time for this project batch was extended to 17 working days. The same analysis also revealed that reducing the batch size could shorten the throughput time for the entire staircase by 4-5 working days. By moving the vertical HVAC installations out of the bathroom to the staircase, the throughput time for the bathrooms could be reduced by 4 working days when looking at the entire batch of apartments produced. However, the schedule review did not reveal any continuous deviations or the root causes of delays, so alongside the traditional schedule review, a quantitative analysis of deviation information produced by day-to-day management was included in this study.

How is the one-piece flow used in the case project to reveal the problems of the production system? (RQ1)

In the researched case, the implementation of 2-hour Takt production based on a LoD400-level plan specific to each apartment type, which 1) standardised materials into pre-cut parts, 2) defined prefabricated components, and 3) fixed the predefined number of parts and materials to be installed according to the M-BOM per location, revealed the weaknesses of upstream processes. This is because, in a 2-hour takt, there is no time for a redesign, acquiring additional parts or materials from the off-site factory or hardware store, or fabricating suitable parts from materials, as was possible in a more stable 4-hour takt in the previous case. Additionally, the precise dimensioning of the prefabricated components and the solutions chosen for tolerance management were not sufficient for all apartments. As a result, workers had to modify and alter prefabricated elements. This led to deviations in dimensions exceeding the tolerances, resulting in either a shortage of parts or materials in that specific takt wagon or a later wagon(s). The skills or available time of the team leaders did not allow for error detection, leading to a build-up of problems. Incorrect decisions made by the workers were caused by a lack of training, lack of printed instructions, and/or design errors due to mistakes made in the upstream processes.

Additionally, there were more takt wagons and workers at the site simultaneously during the project than in the previous one. Each worker had to implement a wagon in three locations equipped with prefabricated elements, parts, and materials. With three 2-hour daily cycles, the worker had to switch workstations (apartments) three times instead of two, as in the previous case. As a result, the team leaders encountered more errors in a day than before. The potential number of errors was also increased due to changes in personnel, alterations to prefabricated elements, partial changes in individual workers' wagons, reorganisation of team leadership, and the addition of new personnel to the order process, as well as the necessity of creating project-specific plans for installations, orders, and prefabrication.

The hierarchy of team leaders, group leader and support organisations were supposed to solve quickly escalated problems. However, the records from the meetings showed that problems began to accumulate from the start of the project, and the root causes of these issues were not resolved; instead, they began to recur. In other words, the one-piece flow highlighted problems. Still, the management arrangement could not conduct adequate root cause analysis or allocate sufficient resources to solve the root cause. The arrangement could only find a temporary solution to the problem and enable work to continue.

Another clear challenge in implementing a one-piece flow was that the latent interdependencies went unnoticed by team members and leaders. This became particularly evident when installing prefabricates, as incorrect installations were made in several apartments before the error was later discovered. A practical example involved installing water pipes in the ceiling, which were implemented as prefabricates. From the ceiling, the pipes continued as surface installations to fixtures such as shower taps, and the error was not detected until wagon 27. However, the incorrect installation was made in wagon 11. In the meantime, 15 incorrect installations have been completed. Various errors forced the project to undertake three Lean interventions. In the first two, the prefabricate installation method was thoroughly reviewed, and team members were defined and trained with precise instructions. In the third, a method for reporting defects was established, and problem sources were identified to make the WhatsApp channel more effective in communicating and resolving defect reports. The first two interventions impacted the number of defects, whereas the third did not appear beneficial, with defect numbers remaining the same despite the intervention.

What are the problems and the root causes in upstream flow revealed by shortening the takt (4h takt to 2h takt)? (RQ2)

The quantitative analysis of the day-to-day management log file revealed that the transition from a 4-hour takt to a 2-hour takt did not go smoothly, with the defect frequency (calculated as the ratio of deviations to the number of takts carried out during the review period) rising from 1,3 defects per takt to 1,9. The categorisation of deviations in the 2-hour takt project is presented in Figure 2. When examining the distribution of deviations, the shift to a 2-hour takt increased the number of product shortages (from 57 to 79 pcs), work errors (54 to 76), and design errors (13 to 20). Still, at the same time, resource allocation (11 to 8) and process errors (42 to 22) decreased. The shorter review period explains the reduction in deviations caused by absences.

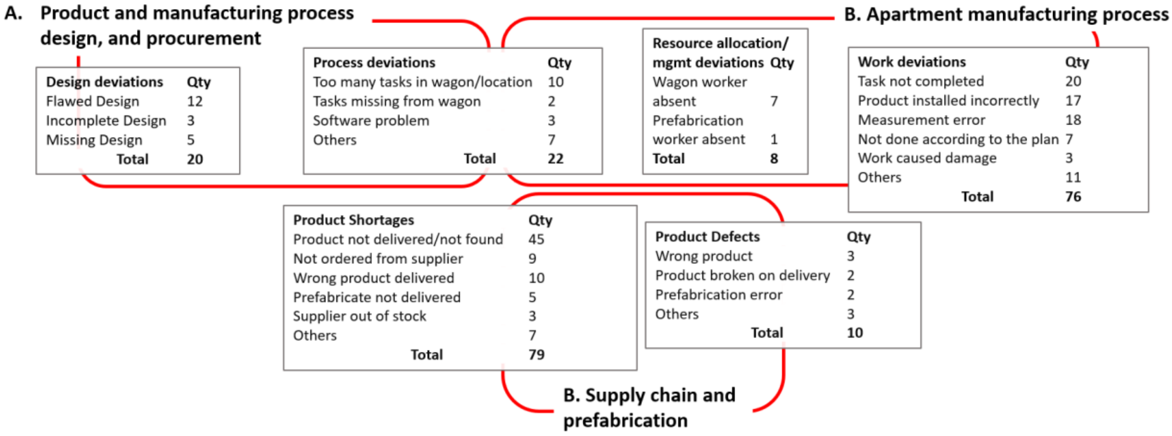

Figure 2: The results from quantitative analysis in the framework of the modelled production system

Process errors decreased because the manufacturing process was shortened in terms of the number of wagons and tasks as prefabrication increased. In other words, the design assumption that the manufacturing process would simplify due to the increased prefabrication seems correct. This is supported by the observation that the majority of process deviations were caused by an excessive number of tasks in individual wagons (levelling failure).

The primary root causes of work-related upstream underperformance can be divided into two categories based on the quantitative analysis of deviations. Work deviations stem from two leading causes: either the work standardisation is inadequate, the guidance is incomplete, or the guidance has not reached the worker responsible for the implementation in the wagon. In such cases, the team member is unaware of the installation instructions, their skill level is insufficient to follow and carry out the installation, or they have decided not to follow the instructions and instead carry out the installation as they consider best.

The supply chain was the weakest part of the production system in terms of the errors that were analysed. The reason is that parties involved in the supply chain lack communication, situational awareness, and verification opportunities in the studied project. Fundamentally, the material is missing because it has been 1) left undelivered to the correct apartment, 2) the wrong material has been delivered instead of the correct one, 3) not ordered or an ordering error has been made, 4) missing because the measurements of the apartment's bathroom exceed the planned tolerance, or 5) the material has already been used elsewhere.

The root cause of design errors is that the 2D drawings are inherently unfeasible, meaning the wagon has been misdesigned. The design may become unviable if a previous wagon has deviated from the implementation plan. Additionally, the drawing may be unfeasible because a measurement deviation in a particular apartment exceeds the established tolerance limits.

When examining process deviations, the most significant factor was the variation in task durations caused by different locations (bathrooms of various sizes). This resulted in what seemed like random overloading of specific wagons. Another reason was that the person did not follow the installation method or could not perform the tasks. At the start of the project, it became apparent that some of the wagon's tasks had been incorrectly planned or were unrecognised and unscheduled. These issues were partially corrected during the commissioning phase of the train by relevelling the wagons.

Based on the root cause analysis, the two most valuable improvements to the production system are transparent management of the supply chain and training team members for their installation tasks. In practice, managing the supply chain means managing the MBOM at the apartment and wagon level, from planned parts through procurement to final installation. For training purposes, the team leaders must study each wagon and its installation tasks themselves to train their team members for wagon-specific implementation and, especially, to lead the work and solve problems effectively. The third area for development is the prefabricates, whose installability must be ensured as part of the training. Since training is challenging to conduct before production starts, the training phase in a 2-hour takt system (i.e., the project start, where the train is brought into a new site) must be resolved either by implementing it at a slower takt, such as a 4-hour takt, or by over-resourcing the teams with additional trainers in the initial phase. The fourth area of development is takt logistics: Just-in-Time (JiT) deliveries divided the shipments into too small batches to track them manually or digitally. Batch size of deliveries should be increased and visual management added to detect deficiencies in delivery contents.

CONCLUSIONS

The primary purpose of this study is to show that rigorous production control requires high quality and flawlessness of the upstream production process. Through a literature review and case study, we formed a one-piece flow production system model from an example project.

The empirical material collected from the case company's renovation projects reveals that modelling the production system made visible the logical components of the production system. Similarly, it made visible the functions associated with these components, the implementation of these functions as processes, and the required and produced information, preconditions for systematic continuous development. This allows the identification of errors and their root causes, whether they need to adjust the product development, the operational model (necessitating correction of the production system), or the dysfunction of the model (necessitating staff training).

In our case study, implementing a 2-hour Takt production from a 4-hour takt revealed a list of new challenges to be eliminated. Therefore, it is validated that the logic of the "sea of inventories", continuously tightening the requirements for the control variable in the production flow, reveals upstream underperformance and drives the elimination of the problems, thus improving efficiency. Overall, our study provides evidence of the applicability of one-piece flow in construction. However, we have only studied a few renovation projects, and further studies need more cases to validate our findings fully. In this context, it is essential to note that the studied business unit and its organisation, which utilises a one-piece flow, is focused solely on executing repetitive projects that inherently involve a lot of repetition. The organisation refers to implementing a one-piece flow as a "housing factory" that flows through projects. Since the one-piece flow is a production system for HVLM products, its applicability to different construction business units is a fundamental topic for further research. Also, various construction project delivery methods must be studied to strengthen the external validity.

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