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HOW A TAKT PLAN CAN FAIL: APPLYING FAILURE MODES AND EFFECTS ANALYSIS IN TAKT CONTROL

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ABSTRACT

Construction projects need adequate planning to set a structure and direction for production, but simultaneously call for effective control to maintain the direction when something unexpected happens. Effective control is of utmost importance for takt production, which is especially vulnerable when disruptions occur. While previous takt production research has primarily focused on how to form a good takt plan, little attention has been given to how to control and continuously improve takt production systems effectively. Addressing the gap, this study inspects takt control through the lenses of failure modes and effects analysis (FMEA). First, we argue that takt control can be perceived through three different failure categories: failures within wagons, failures in handoffs, and failures in takt trains. We discuss the peculiarities of takt control through these categories and provide examples of failures with their respective failure mode(s) and possible control action(s). Second, we construct an FMEA-based framework for effective takt control that shows how to recover from failures and avoid them altogether. Future research may consider validating the failure categories and the framework through case studies or simulations, and examining their applicability in supporting digital takt production.

KEYWORDS

Lean construction, takt production, failure modes and effects analysis (FMEA), production planning, production control

INTRODUCTION

Takt production is a location-based method for planning, controlling, and continuously improving construction production systems (Lehtovaara et al. 2021). It has gained elevated attention in the last fifteen years or so among construction management professionals and scholars. Takt production focuses on planning production to advance with a consistent beat, or 'takt', vigorously controlling production to maintain the beat,

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and continuously improving the system as problems or learning opportunities arise (e.g., Frandson et al. 2013). The increased interest in takt production comes for a reason, as previous studies have reported several benefits from its application. These benefits include decreased production durations (Binninger et al. 2018), increased production transparency and stability due to clarity of handoffs (Frandson et al. 2014), and a more proactive touch to solving and controlling problems (Linnik et al. 2013).

Despite this increased interest, previous studies have focused mainly only on planning, but control and continuous improvement during execution have been addressed in a somewhat superficial manner (barring exceptions such as Binninger et al. 2017 who attempted to codify different takt control mechanisms). This is surprising as the success of takt production is determined in execution; takt production is especially prone to disruptions, requiring constant attention to controlling production and steering in order to adhere to the predetermined plan (e.g., Alhava et al. 2019). This study explores these peculiarities and constructs a framework for takt control to address them. We approach this exploration by combining failure modes and effects analysis (FMEA) thinking with takt production.

Widely used in several industries and especially in manufacturing operations since the 1950s, FMEA offers a structured approach to recognizing and evaluating different failures and failure modes, studying their consequences, and identifying means to address them (ASQ n.d). Failures are the consequence of the occurrence of errors or defects (e.g., a task finished late), while failure modes denote the possible ways of something "going wrong," i.e., what causes the failure (e.g., insufficient resources to finish a task on time). Aiming to minimize waste and value loss, FMEA is commonly used in the design and control stages of processes or products, ideally applied through their lifecycle to cultivate continuous improvement. In construction management, FMEA has been applied, e.g., in design process management (Andery et al. 2000), in innovation implementation (Murphy et al. 2011), and in production management (Bahrami et al. 2012). Construction failures include, e.g., tasks finishing late or too early, quality defects, or waste caused by excess movement or material transportation. Such failures may be caused, e.g., due to a crew's inability to complete planned tasks, poor planning, inherent uncertainty (Wehbe & Hamzeh 2013), inadequate commitment, or unsolved conflicts between parties during planning or execution (Iyer & Jha 2006).

For process design and control, FMEA follows these steps (e.g., Grout 2007), illustrated in Figure 1: (1) assemble a cross-functional team to perform analysis, (2) identify (potential or existing) failures and their related failure modes through brainstorming or process tracking, (3) identify (root)causes of the failures, identify (potential or existing) consequences of the failures, their occurrence rating and severity quantitatively or qualitatively, and (4) determine and implement countermeasures to manage adverse effects of failures and/or their occurrence in the future. The concept of mistakeproofing can further help categorize the possible countermeasures (Tommelein & Demirkesen 2018). Elimination or prevention of failures should happen in early process stages, before any failure might occur; in contrast, detection or mitigation could help identify countermeasures after a failure has occurred.

FMEA may provide an interesting complementary process for takt production, as takt production by its nature puts the production system in a stress test. On the one hand, takt production aggressively reveals failures and failure modes as they occur, urging for continuous problem-solving. On the other hand, FMEA provides a way to systematically spot problems that are surfaced during takt production and enables learning so that the recurrence of such problems may be reduced if not altogether eliminated. Thus, FMEA could increase the effectiveness of a production system that uses takt, nurturing both control and continuous improvement functions. To support our aim, namely to explore the peculiarities of takt control and construct a framework for takt control to address them, we pose two research questions: "*In which ways can takt plans fail?*" and "*How could these failures be recovered from, or avoided in the first place?*"

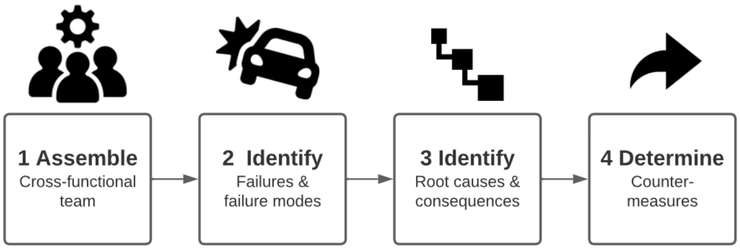

Figure 1: General FMEA process

This paper is structured as follows. First, we state the necessity of effective planning and control system in construction projects and introduce some of the most recent lean construction approaches used for planning and control. Second, we discuss the peculiarities of takt production, categorize possible takt production failures, and provide examples of possible failures, failure modes, root causes, and control actions in the context of takt production. Third, we present an FMEA framework for takt control that shows how to recover from failures and proactively avoid them. Last, we discuss the study contributions and possible future research avenues.

CONSTRUCTION PLANNING AND CONTROL

Construction projects are directed by plans generated at the early stages of their lifecycle. **Production planning** sets a structure for the project's execution, determining what needs to be done, when, and with which kind of resources (Vollman et al. 1997). However, making good plans does not guarantee success. While plans are necessary to envision the initial direction for production, they are merely forecasts, doomed to fail at some point during execution. Therefore, **production control** is needed. Control entails making changes to a predetermined plan when something unexpected or unforeseen happens, and new opportunities arise. Unpredictability is innate to complex systems (such as construction production) as the behavior of such systems can never be precisely anticipated beforehand (Snowden & Boone 2007). Arbulu et al. (2016) argue that to be effective, production control systems should constantly sense, analyze, and respond to any issues that surface. Moreover, control should be seen as a driving force for future direction to meet the customer's expectations (Drucker 1974), and the changes made should be informed by the project's overall goals.

Even though forward-looking production control is employed widely in other domains (such as in manufacturing), it is not so present in construction production practice; instead, the focus is on measuring what has been done to assess conformance to plan. Construction management practices tend to be based on the idea that the original plan should be an adequate pathway for production, with little need for adjustment during execution. This approach originates from the use of Critical Path Method (CPM; Kelley & Walker 1959) and Program Evaluation and Review Technique (PERT), which were created to focus on financial- and progress reports at the project level rather than to steer future direction on the production level effectively. Koskela and Howell (2001) and

Laufer and Tucker (1987) raise a concern that, when ignoring the production control aspect, a site manager's focus is put on producing reports and articulating justifications for past failures rather than proactively addressing them.

Next, we present some of the most studied and recent lean construction approaches to effective production management that entail control in addition to the planning function.

LEAN CONSTRUCTION APPROACHES TO PRODUCTION PLANNING AND CONTROL

The field of lean construction has produced various planning and control approaches for effective construction production, with the **Last Planner® System** (LPS; Ballard and Tommelein 2021) being arguably one of the most widely studied ones. LPS is based on conducting planning and control through converging horizons as the execution of work gets closer; tight collaboration with those who execute the work; revealing and removing constraints; making reliable promises by committing to what has been agreed; creating reliable handoffs; and pursuing continuous improvement by learning from problems (Ballard et al. 2009). The LPS process is divided into five steps. The first two (master level planning and phase planning; describing what "should" be done) consider production preparation and planning, while the latter three (lookahead planning, commitment planning, and learning; respectively describing what "can", "will", and was done ("did")) focus on executing, controlling, and improving the production system. During execution, control and continuous improvement actions are supported by "daily huddles" in which prerequisites and possible barriers for work, as well as learning opportunities, are collaboratively addressed (Ballard and Howell 2003).

Another widely studied lean construction planning and control approach is the **Location Based Management System** (LBMS; Kenley & Seppänen 2010). Seppänen et al. (2010) argue that LBMS and LPS complement each other when simultaneously implemented in production control. As LPS focuses on initiating discussions and reliable promising, LBMS produces a complementary counterpart by providing a systematic, data-based work structuring and production control method. Seppänen et al. (2010) reported that when combined, LBMS tracking data can support LPS control steps by providing forecasts and triggering early warnings in structured graphical and numerical format. This feedback can then be used as input for collaborative decision-making during the control process.

Previous LBMS studies (e.g., Seppänen 2009) have also considered possible failures and failure modes (however, these exact terms were not used), and their respective control actions in the (lean) construction planning and control context. Possible failures include deviations in production rates, start-up delays, and work being split into multiple areas; possible failure modes include a preceding task starting late, crew demobilization, interruption of work, or wrong order of locations or work sequence (Seppänen & Kankainen 2004, Kenley & Seppänen 2010). Possible control actions consist of adjusting the production rate (e.g., add or reduce resources, work overtime), steering the plan (e.g., change process logic, create a new task, split tasks, re-sequence work, review task data), or suspending the work (Kenley & Seppänen 2010).

TAKT PRODUCTION AND FMEA

Generally speaking takt production is more similar than different from other lean construction planning and control approaches. Frandson et al. (2014) mention that, similarly to LBMS, takt production can be used with LPS while providing synergies to each other. The 2020 LPS benchmark (Ballard and Tommelein 2021) also situates takt planning as a method in the system. Whereas takt production provides a way for work structuring that actively supports good production flow, LPS offers a sound production system structure with tangible horizons for planning, control, and continuous improvement. Even though using slightly different concepts and terminology, Dlouhy et al. (2016) also describe a similar combined process for takt production, called "Takt Planning and Takt Control" (TPTC). Their three-level process (with macro, norm, and micro levels) shares characteristics with LPS horizons. The first level is similar to master level planning, the second with lookahead planning, and the last with commitment planning and learning.

Despite similarities with other control methods, some unique characteristics of takt production (especially affecting the emergence of failures and failure modes and their control) should be considered before applying the aforementioned LPS and LBMS practices to takt production. Possible takt production failures can be categorized into three groupings that also reflect the peculiarities of takt production (Figure 2): (1) wagon content failures (corresponding to failures in a process step), (2) wagon handoff failures (failures between process steps), and (3) takt train failures (failures affecting the whole process, possibly causing cascading effects). The reason to group failures and failure modes into these categories originates from the idea of takt wagons being the fundamental units (Dlouhy et al. 2016) that set a base for work structuring in takt production. Inspecting these units, their interfaces (handoffs), and combinations of them (trains) provide a tangible and visual way of addressing FMEA in a takt production context.

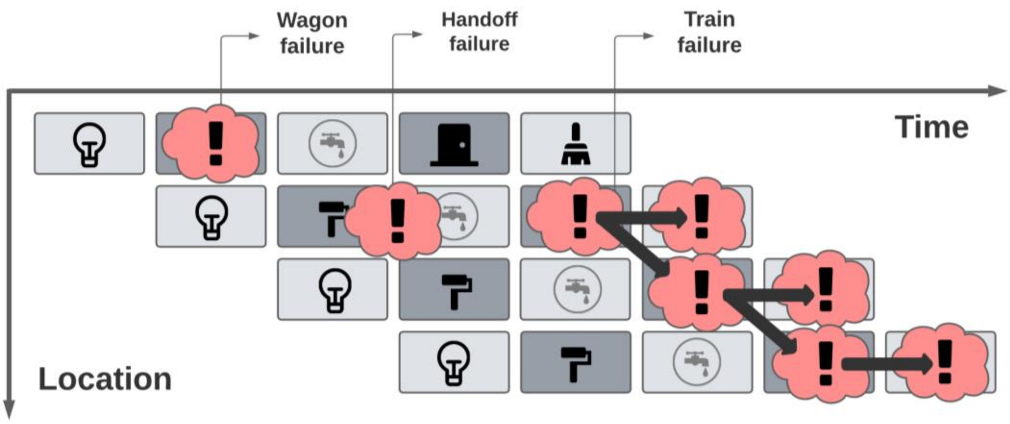

Figure 2: Wagon, handoff, and train failures

WAGON CONTENT FAILURES AND CONTROL

A takt wagon is the batch of tasks to be completed in a specified takt area within a given takt time. Controlling wagon content tightly in short intervals is necessary to avoid failures within wagons, such as unfinished tasks or tasks finishing late. Reducing batch sizes over time is often characteristic—though not required—for takt production systems. Small batch sizes can be employed to adjust the speed of the process in order to meet the (externally provided) milestones, and to provide an increased opportunity to identify opportunities for improvement. Small batch sizes further increase the need for tight wagon content management (Haghsheno et al. 2016), but also possesses particular advantages. Problems are constantly surfaced (while being visible to everyone), creating an opportunity to actively act on them within wagons before they significantly harm other parts of the production system. Here, rigorous and collaborative management practices (such as daily huddles) are necessary to enable timely failure (and failure mode) identification and control. Successful wagon content management can increase production reliability and reduce overall production risks (Haghsheno et al. 2016).

WAGON HANDOFF FAILURES AND CONTROL

Successfully managing the interfaces between wagons is critical for takt production's success (Frandson et al. 2015) and for production in any Parade of Trades (Tommelein et al. 1999). Therefore, in addition to intensive wagon content control, takt control calls for effective wagon handoff control because that reliably enables the work to begin in the next wagon. The inability to meet a timely handoff with the needed quality produces failures, such as missing preconditions for work, will affect the next crew's work immediately. This visible and immediate effect creates an urge for make-ready work, putting social pressure on crews to pay increased attention to wagon handoffs (Frandson et al. 2013).

A central element of takt planning in achieving reliable wagon handoffs is favoring capacity buffering (Frandson et al. 2015). In contrast to other lean control methods (such as LBMS), rather than fully loading crews resources and minimizing their downtime with excess time and space buffers (maximizing their utilization by avoiding "workers waiting for work"), in takt production crew resources are underloaded[4] by employing standby capacity (avoiding "work waiting for workers") (Linnik et al. 2013). Standby capacity provides additional means for achieving timely handoffs, as it makes it possible to absorb variability when needed, and when not needed the spare capacity can be used for quality assurance, problem-solving, or self-development (Tommelein 2020). Wagon handoff management is also a key enabler for effective wagon content control, enabling tasks to start (and finish) timely within the next wagon.

TAKT TRAIN FAILURES AND CONTROL

Takt control focuses on achieving a stable process flow that produces products in synchronization with the client's needs (Frandson et al. 2014). This flow should be maintained through the whole sequence of takt wagons progressing through takt areas; such sequences are called takt trains. Takt train failures are primarily caused by system-level failure modes such as an illogical production sequence or missing design information. These can cause wagon and handoff-related failures to accumulate (Seppänen (2009) refers to "cascading delays" and Dahlberg & Drevland (2021) to a "parade of delays") or cause the system to dysfunction as a whole, such as by generating a large amount of resource fluctuation.

Possible takt train control actions include, for example, pull-planning of supporting flows such as information and material flows (Lehtovaara et al. 2021) to support production reliability and prevent making-do (Koskela 2004); decoupling of logistics management from the crews' onsite work by using logistics operators and kitting of materials (Tetik et al. 2019); or stopping the train as a whole in the case of an accumulated failure until the causes are fixed altogether. Also, the aforementioned standby capacity as a buffering mechanism offers a powerful way of increasing the overall production performance and flow (Horman & Thomas 2005) while reducing the possibility of minor problems accumulating into a train failure.

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[4] Court (2009) and Frandson et al. (2015) suggest that underloading to 75-80% of needed capacity can serve as a general rule of thumb.

FAILURE, FAILURE MODE, ROOT CAUSE, AND CONTROL ACTION EXAMPLES

Figure 3 lists some possible failures, failure modes, root causes, and control actions related to the aforementioned three categories. These examples are drawn from previous lean construction and takt production studies (e.g., Binninger et al. 2017, Seppänen 2014), and complemented by the authors' own takt implementation experiences. The provided list is not exhaustive but is to serve as a guiding example for readers as they encounter failures in their takt implementation initiatives. Next, we present a framework that illustrates the FMEA process in practice.

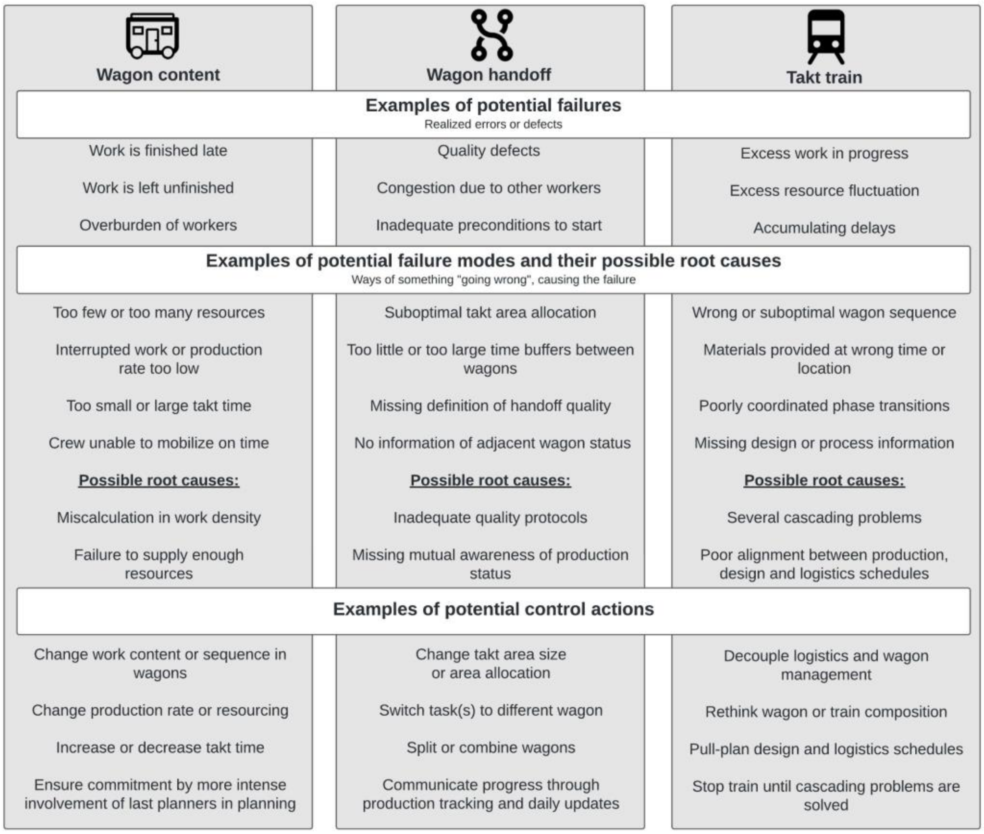

Figure 3: Examples of failures, failure modes, root causes, and control actions

FMEA FRAMEWORK FOR TAKT CONTROL

Based on the needs of construction production systems in general, insights from previous lean construction approaches to planning and control, and the peculiarities of takt production, the proposed FMEA framework for systematic takt control is presented in Figure 4. The framework combines the FMEA process with the planning and control horizons of the presented lean construction approaches, which can be applied to takt production context. The framework consists of four phases: (1) preparation, (2) FMEA problem-solving during planning and (3) during the control of production, and (4) post-analysis. It should be noted that the framework does not aim to replace the existing takt planning and control methods, but rather to serve as a support tool for them, whenever the combination of LPS and takt (Frandson et al. 2015) or a three-level method (Dlouhy et al. 2016) is employed.

In the **preparation stage** (that occurs during master planning or at the macro level), a cross-functional team (consisting of site/project managers, site crews, and other relevant stakeholders for production planning and control such as design or logistics managers) is formed to carry out the FMEA process. The master plan provides a basis to guide detailed production planning and control, and simultaneously, the FMEA process provides feedback for steering the master plan as needed. FMEA can also be used in the preparation stage for a project-level risk analysis to proactively address possible shortcomings of the master plan.

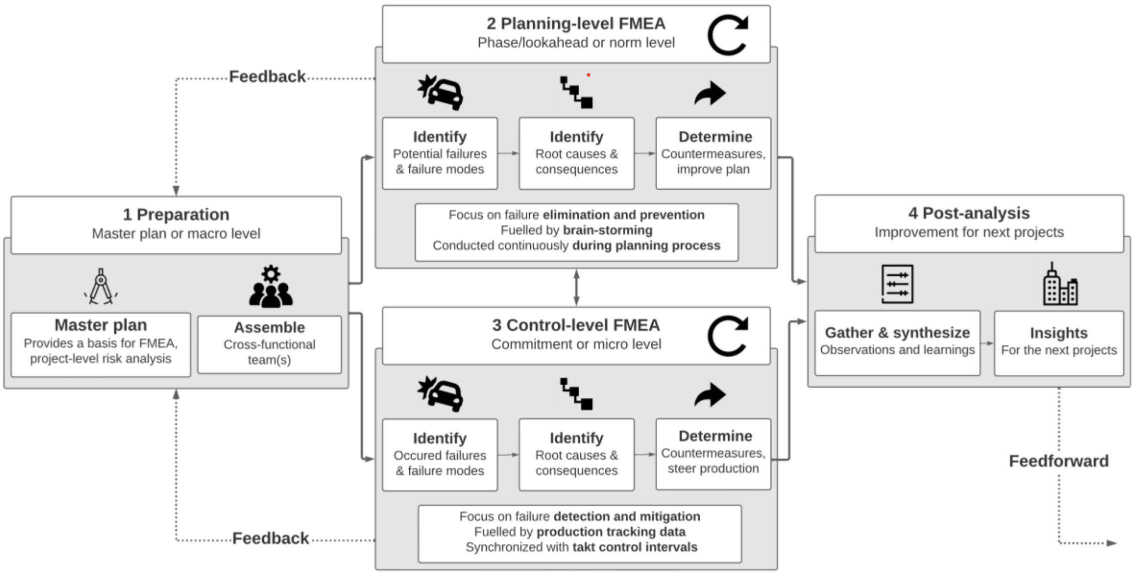

Figure 4: FMEA framework for systematic takt control

In the **planning stage** (that occurs during phase/lookahead planning or at the norm level), a detailed analysis is conducted in which failures and failure modes are identified and proactively eliminated or prevented before the production execution. The consequences of the identified (root)causes are analyzed by weighing their severity, assessing their likelihood of occurrence, the possibility for accumulating effects, and the timeliness and cost of possible control actions. FMEA is conducted through collaborative brainstorming and can done during ongoing production preparation meetings or workshops. Preferably, the FMEA process should be done on a whole production level but also individually for every wagon and takt area. Failure modes for two different wagons can be the same, but their effects and control efforts may vary. For example, the employment of buffers should be based on each wagon's unique characteristics, such as possible variability.

In the **control stage** (that occurs during commitment planning or at the micro level), the realized failures and related failure modes are identified from production tracking data. Tracking data serves as a catalyst for collaborative identification of (root) causes and determining adequate actions (to detect and mitigate the failure effects) during daily/weekly takt control meetings. For example, a failure to finish work on time within a wagon should trigger a discussion that aims to identify the failure mode (e.g., insufficient resources) and the root cause of the failure (e.g., inadequate involvement of workers in production planning), followed by deciding a corrective action to ensure production gets back on track (e.g., increase resources or increase takt time). Simultaneously, actions for eliminating or preventing the failures from happening again should be discussed and implemented (e.g., initiate additional takt training for workers).

In the **post-analysis stage** (that occurs continuously during or after production), learning from identified failures, failure modes, their root causes, and other relevant observations from production tracking data are collected and synthesized with the cross-functional team. The synthesis should be leveraged when preparing the upcoming projects or project stages, proactively aiming to eliminate and prevent similar failures in the future. For example, changing batch size could be an immediate control action but also a possible corrective action for the next project phase or the following project.

Even though the framework focuses on takt control, it inevitably extends to takt planning and continuous improvement, highlighting the interconnectedness of these functions; notably, the presented examples in Figure 3 could be identified and solved in every stage, either by preventing or eliminating them (preparation or planning phases) or detecting and mitigating them (control phase). Effective control feeds from the preparation and planning stages while offering feedforward for future takt planning. Use of the framework can provide a systematic path for effective organizational learning, development of organizational capabilities, and for reaching higher maturity levels of takt implementation (Lehtovaara et al. 2020).

STUDY CONTRIBUTION AND FUTURE RESEARCH

To answer the first question "*In which ways can takt plans fail?*" we categorized takt production failures as (1) failures within wagons, (2) failures in handoffs, and (3) failures in takt trains. We discussed the peculiarities of takt production related to these categories and provided examples of failures, their respective failure modes, root causes, and possible control actions. To answer the second question "*How could these failures be recovered from, or avoided in the first place?*" we constructed a framework for takt control that uses the FMEA process logic.

For practitioners, the study offers a systematic guideline for problem-solving in a takt control context that can be combined with their preferred takt production method. In addition, examples of failures, failure modes, root causes, and control actions can feed practitioners' imagination in applying the framework in action. For scholars, the study offers a novel view by approaching takt control through the lenses of FMEA, offering an interesting point of departure for future research.

More specifically, we identified two distinct future research avenues. First, as the failure categories and the framework are based on a conceptual study, they call for validation. The validation could be done through case studies, simulations, or expert surveys to gain insights for the framework's practical applicability. Case studies and simulations could also serve as a basis for objectively assessing the magnitude of different failures and failure modes and the effectiveness of their related control actions. Similar studies have already been conducted in the context of LBMS (e.g., Seppänen & Kankainen 2004). Constructing a comprehensive library of failure and failure mode examples through validation could also serve practitioners in identifying additional solutions for takt control in their specific context. However, one should bear in mind that even though similarities among takt production initiatives exist, each different organization and project will always require a unique examination of its failures, failure modes, and their effects grounded on their contextual needs. One should also note the magnitude of number of failures and failure modes that can exist. In practice, it may well be that the number of possible failures and failure modes is larger than those presented through the illustrative examples, possibly exceeding dozens or even hundreds of different variations. Thus, it would also be interesting to identify which elements are generalizable and which are unique for specific project contexts. This would help inform the learning process and determine which practices can be standardized vs. which need to be individually considered for every given situation.

Second, it should be examined if the framework can provide a platform for structured and automated data collection and analysis, supporting digital takt production (Peltokorpi et al. 2021). For effective digital takt control, detailed (in granularity of hours and minutes, instead of days and weeks) data collection and analysis are needed to feed the FMEA process effectively. Digital takt control could further serve as a building block for digital twin concepts (Sacks et al. 2020), data-driven learning, and systemic change.

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