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# DO FAILURES IN A TAKT PLAN FIT THE FMEA FRAMEWORK?

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## ABSTRACT

Few studies have explored takt planning failures and how they might be better prevented. Recently Failure Modes and Effects Analysis (FMEA) has been proposed as a framework for actively preventing failure in takt planning projects. This project tests case study failures against the proposed FMEA framework as a first step to determine whether a FMEA-takt plan framework can help identify and respond to takt plan failures. In this case study, takt planning was implemented halfway through the construction of five large data centers in Utah, USA. The project was repetitive, enabling a takt of one day despite the large size of the project. Any variance from the schedule (a takt plan failure) was associated with a specific task and marked in their weekly work plans (WWPs). A reason for the variance was identified. These variances were compiled for all available WWPs and are compared to the failure categories proposed in the FMEA-takt plan framework. This study shows that the FMEA-takt plan framework is feasible with minor adjustments to account for failures in takt plans that are due to variables that are beyond the scope of a takt plan, such as unforeseen conditions or extreme weather.

## KEYWORDS

FMEA, process, takt planning (TP), variability, work flow.

## INTRODUCTION

Over the last ten years, takt planning has been developed and applied in the construction community. Starting with Frandson et al. (2013) detailing takt planning, research has been conducted with the goal of understanding its impact and value in reducing variability and improving efficiency.

As research continues to explore takt planning, the question becomes why does it continue to be an area of focus for academia, and why does it work well? Takt planning is especially effective because it emphasizes eliminating bottlenecks, resulting in a decrease of compounding delays (Tommelein et al., 2022). Takt gives immediate feedback which allows for early recognition of whether the project is running according to schedule or behind schedule. Takt increases transparency but it also structures work which allows for an easy understanding of next steps (Frandson & Tommelein, 2014; Kujansuu et al., 2020). Takt time reduces throughput time and enables projects to finish in shorter amounts of time (Binninger et al., 2017). Takt has great benefits, however it requires significant effort at the start of the project and dedication to maintain it throughout the project (Frandson et al., 2013). Due to this effort, when takt plan

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failures occur it can be harder to keep the takt plan through to the end of the project (Alhava et al., 2019).

Takt plans have been compared with other scheduling methods, and recently combined with a Failure Modes Effects and Analysis (FMEA) framework to better combat failures that occur within a takt plan. FMEA is a method for identifying possible errors in a system or process with the goal of better avoiding the errors in the future (Carbone & Tippett, 2004). FMEA has been used in other industries, such as medicine and manufacturing to improve complex processes and has the potential to greatly benefit production control methods in construction. Lehtovaara et al. (2022) outlined how to apply FMEA to takt plans.

This paper specifically focuses on testing the categorization of takt plan failures within the FMEA framework outlined by Lehtovaara et al. (2022). In their paper, they defined three failure categories for a FMEA-takt plan framework: wagon content failures, wagon handoff failures, and takt train failures. Wagon content failures occur within a wagon or one trade. Wagon content failures result from overburdened workers, a lack of materials, or missing equipment. Wagon content failures are limited to the trade and task that they affect. Wagon handoff failures are failures that impact the turnover of a takt area from one trade to another; these may include quality defects or the prior trade being late to handoff the area. Wagon handoff failures impact the shift between trades or tasks, but do not impact the project and takt plan success as a whole. The last type of failure defined by Lehtovaara et al. (2022) is a takt train failure. Takt train failures impact the whole project; this may include significant scheduling and coordination errors or compounding delays in wagon handoffs. Each failure may lead to a further failure, thus the FMEA framework aims to resolve takt planning failures before they cause a takt plan to fail. If the FMEA framework proves effective in categorizing takt plan failures, the rest of the steps outlined by Lehtovaara et al. (2022) can be applied to a takt plan. The FMEA framework has the potential to greatly decrease takt plan failures and therefore increase takt plan success.

The research was guided by the hypothesis that the FMEA-takt plan network will cover all identified types of failures within a takt plan. This paper applies the FMEA framework for identifying types of failures in a takt plan outlined by Lehtovaara et al. (2022) to a large scale, repetitive project, with the goal of determining the effectiveness of the framework in classifying failures within a takted project. The FMEA-takt plan framework has not been tested empirically. This paper seeks to begin the process of testing the FMEA framework by determining whether failures in a takt plan case study project fit the failure categories proposed by the FMEA framework.

# LITERATURE REVIEW

## TAKT TIME PLANNING

Takt time is often associated with the manufacturing industry, however its use in the construction industry dates back to the construction of the Empire State Building (Frandson et al., 2013). Its goal is to produce based on customer demand or the desired time frame of the customer (Haghsheno et al., 2016; Hopp & Spearman, 2008). It has proven more difficult to apply takt to construction than manufacturing for a variety of reasons. Most notably, construction happens on a much larger scale. For takt, construction may be considered a form of low-volume high-variety manufacturing so the takt time is typically a few days or one week as opposed to one minute (Ricondo Iriondo et al., 2016; Tommelein et al., 2022). Takt can be revolutionary since it increases both flow and transparency. Increasing flow and transparency levels the playing field on site or prioritizes all the contractors and trades equally and gives them equal opportunity to complete their work effectively (Koskela, 1992). Although similar to other methods that increase flow (LPS, LBMS), takt differs because it focuses on creating capacity buffers and decreases variability by providing consistency in turnover rates (Ballard, 2000; Seppanen & Kankainen, 2004; Tommelein et al., 2020). Frandson et al. (2013) proposed a method for planning and production control, takt planning. Takt planning allows takt to be applied to construction systematically.

Case studies have supported the value of takt planning as a method for construction production planning and control. Apgar et al. (2022) found that takt planning reduced planned and actual construction durations up to ~70% of the total workdays. A similar case study with a large, repetitive style project concluded that takt planning reduced project duration by 50% (Yassine et al., 2014). Binninger et al. (2018) conducted a case study and came to the same conclusion: takt planning significantly decreases construction duration. Even in cases where the takt was lost by the end of the project, takt planning decreased project cost, increased quality, and decreased throughput times (Alhava et al., 2019). In addition, takt aids in creating flow in the construction process, specifically within the trades (Kujansuu et al., 2020). However, despite these studies demonstrating the effectiveness of takt planning, further research is needed. Takt planning applies to the construction process with the goal of continuous improvements. More research should be conducted with a focus on how continuous improvements can be made to takt plans during the construction process (Lehtovaara et al., 2020).

## Failures in Takt plans

Variability has always been at the forefront of research in lean construction since it is the enemy of reliability and productivity. For example, Tommelein et al. (1999) presented the Parade Game to teach students (and others) about the impact variability within and between trades has on the timeline of a project. The Parade Game effects teaches about variability in construction since it shows how having an inconsistent turnover rate frequently results in delays or other problems (Tommelein et al., 1999). Flow systems, such as takt plans, seek to create consistent turnover rates. However, this does not mean there is no variability in flow systems. Variability leads to failures; research into takt plan failures is research into variability. There is a lack of research regarding failures in flow systems, but other literature discusses reasons behind failures in scheduling. Some of these reasons include ignorance, weather, unique project nature, and lack of belief in scheduling methods among workers and management (Iyer et al., 2006; Muhammad et al., 2020). Weather is a common cause for scheduling failures in projects in the United States (Liu et al., 2021).

Research on takt planning investigates methods for preventing failures or reacting to failures but few apply these theories to case studies. Dlouhy et al. (2016) explored project management through a related method for production control, takt planning takt control (TPTC), that follows the project past the production stage. Application of TPTC resulted in a case study project reducing their construction time from eleven months to five months (Dlouhy et al., 2016). A recent case study described how unreliable workflow leads to greater waste by preventing the greatest possible production capacity and that increased transparency prevents delays (Dahlberg et al., 2021). Although takt plans result in greater construction efficiency, due to takt plan failures, the takt plans often take longer than planned. Real construction rates are approximately 20% slower than what is planned (Binninger et al., 2019). Dahlberg et al. (2021) proposed that weekly meetings and daily huddles are proactive steps to decreasing failures in takt planning. Binninger et al. (2017) identified 31 adjustment measures to increase flexibility in takt planning and decrease the impact of failure on the project. Most recently, Lehtovaara et al. (2022) applied FMEA methods to takt planning to better classify and proactively counter failures. Further understanding of failures in takt planning in practice is necessary for better scheduling and for improvements in project control systems such as takt planning, LBMS, and LPS (Ballard, 2000; Lehtovaara et al., 2022; Seppanen & Kankainen, 2004).

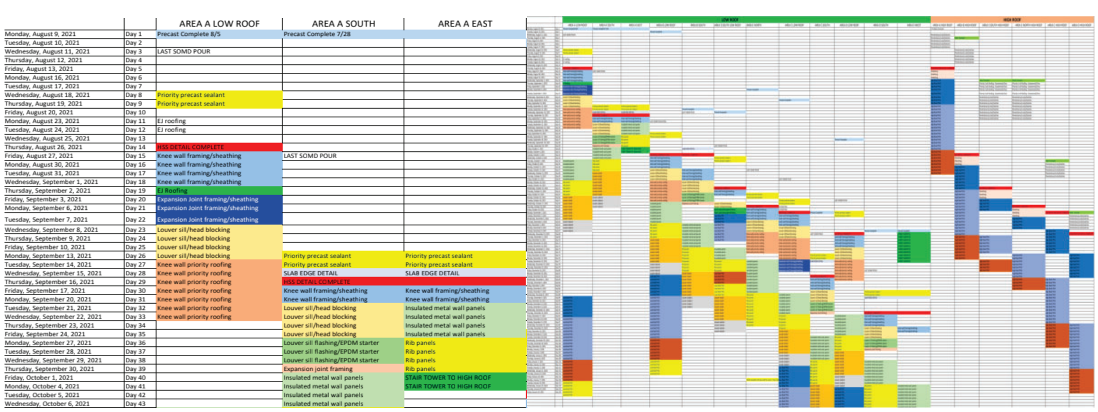
As presented by Lehtovaara et al. (2022), the FMEA method can be applied to takt planning to follow the takt plan through its lifespan and help with continuous production control and decreasing failure frequency. This is not the first time that FMEA has been applied to construction planning methods; FMEA was explored in construction in relation to the Last Planner System (Wehbe & Hamzeh, 2013). However, a detailed understanding of FMEA's utility in construction has yet to be realized. FMEA's usefulness has been demonstrated in other industries such as medicine and manufacturing (Bahrami et al., 2012). FMEA works well with takt planning since FMEA aims to result in action before any failures occur and takt planning increases transparency to enable improvement in the takt plan throughout construction (Bahrami et al., 2012; Lehtovaara et al., 2022).

# METHODOLOGY

## CASE STUDY

A case study was conducted to assess the applicability of the takt planning FMEA framework as outlined by Lehtovaara et al. (2022). Applying the FMEA-takt plan network to a case study project, bridges the gap between the theoretical and practical value of FMEA in takt planning. Not only is a case study a valid method for determining the validity of the FMEA takt planning framework, but in general case studies are valuable because they allow theories to be studied in their natural environment, possibly revealing new information that would remain undiscovered otherwise (Crowe et al., 2011). This case study was conducted using data from one project; Hartmann et al. (2008) demonstrate how a single case study has been used as an effective research methodology. Additionally, Lehtovaara et al. (2022) specifically call for validation of their theories via case studies and more in-depth research about failures within takt plans via case studies. This paper seeks to fill both research gaps.

The case study for this project followed a large data center project in Utah, USA, where five large data centers have been constructed, three of them being planned and scheduled using a takt planning system (Apgar et al., 2022). The case study project implemented a takt time of one day to enable a quicker throughput and a higher level of detail in the planning stage of the project (Apgar et al., 2022). Figure 1 shows a takt plan used in the case study project. Each row on the schedule corresponds to a workday and each row to a project work area. It is important to note that although a takt of one day was chosen, depending on the task, some trades worked in the same area for more than one day. The takt time was maintained by highly detailed schedules working to maintain a consistent beat despite this fact. In addition, the case study implemented pieces of the Last Planner System, such as Weekly Work Plans (WWPs), to guide the focus on pull planning during schedule creation (Ballard, 2000).



| | | AREA A LOW ROOF | AREA A SOUTH | AREA A EAST |
|---|---|---|---|---|
| Monday, August 9, 2021 | Day 1 | Precast Complete 8/5 | Precast Complete 7/28 | |
| Tuesday, August 10, 2021 | Day 2 | | | |
| Wednesday, August 11, 2021 | Day 3 | LAST SOMD POUR | | |
| Thursday, August 12, 2021 | Day 4 | | | |
| Friday, August 13, 2021 | Day 5 | | | |
| Monday, August 16, 2021 | Day 6 | | | |
| Tuesday, August 17, 2021 | Day 7 | | | |
| Wednesday, August 18, 2021 | Day 8 | Priority precast sealant | | |
| Thursday, August 19, 2021 | Day 9 | Priority precast sealant | | |
| Friday, August 20, 2021 | Day 10 | | | |
| Monday, August 23, 2021 | Day 11 | EJ roofing | | |
| Tuesday, August 24, 2021 | Day 12 | EJ roofing | | |
| Wednesday, August 25, 2021 | Day 13 | | | |
| Thursday, August 26, 2021 | Day 14 | HSS DETAIL COMPLETE | | |
| Friday, August 27, 2021 | Day 15 | Knee wall framing/sheathing | LAST SOMD POUR | |
| Monday, August 30, 2021 | Day 16 | Knee wall framing/sheathing | | |
| Tuesday, August 31, 2021 | Day 17 | Knee wall framing/sheathing | | |
| Wednesday, September 1, 2021 | Day 18 | Knee wall framing/sheathing | | |
| Thursday, September 2, 2021 | Day 19 | EJ Roofing | | |
| Friday, September 3, 2021 | Day 20 | Expansion Joint framing/sheathing | | |
| Monday, September 6, 2021 | Day 21 | Expansion Joint framing/sheathing | | |
| Tuesday, September 7, 2021 | Day 22 | Expansion Joint framing/sheathing | | |
| Wednesday, September 8, 2021 | Day 23 | Louver sill/head blocking | | |
| Thursday, September 9, 2021 | Day 24 | Louver sill/head blocking | | |
| Friday, September 10, 2021 | Day 25 | Louver sill/head blocking | | |
| Monday, September 13, 2021 | Day 26 | Louver sill/head blocking | Priority precast sealant | Priority precast sealant |
| Tuesday, September 14, 2021 | Day 27 | Knee wall priority roofing | Priority precast sealant | Priority precast sealant |
| Wednesday, September 15, 2021 | Day 28 | Knee wall priority roofing | SLAB EDGE DETAIL | SLAB EDGE DETAIL |
| Thursday, September 16, 2021 | Day 29 | Knee wall priority roofing | HSS DETAIL COMPLETE | |
| Friday, September 17, 2021 | Day 30 | Knee wall priority roofing | Knee wall framing/sheathing | Knee wall framing/sheathing |
| Monday, September 20, 2021 | Day 31 | Knee wall priority roofing | Knee wall framing/sheathing | Knee wall framing/sheathing |
| Tuesday, September 21, 2021 | Day 32 | Knee wall priority roofing | Louver sill/head blocking | Insulated metal wall panels |
| Wednesday, September 22, 2021 | Day 33 | Knee wall priority roofing | Louver sill/head blocking | Insulated metal wall panels |
| Thursday, September 23, 2021 | Day 34 | | Louver sill/head blocking | Insulated metal wall panels |
| Friday, September 24, 2021 | Day 35 | | Louver sill/head blocking | Insulated metal wall panels |
| Monday, September 27, 2021 | Day 36 | | Louver sill flashing/EPDM starter | Rib panels |
| Tuesday, September 28, 2021 | Day 37 | | Louver sill flashing/EPDM starter | Rib panels |
| Wednesday, September 29, 2021 | Day 38 | | Louver sill flashing/EPDM starter | Rib panels |
| Thursday, September 30, 2021 | Day 39 | | Expansion joint framing | Rib panels |
| Friday, October 1, 2021 | Day 40 | | Insulated metal wall panels | STAIR TOWER TO HIGH ROOF |
| Monday, October 4, 2021 | Day 41 | | Insulated metal wall panels | STAIR TOWER TO HIGH ROOF |
| Tuesday, October 5, 2021 | Day 42 | | Insulated metal wall panels | |
| Wednesday, October 6, 2021 | Day 43 | | Insulated metal wall panels | |

Figure 1: Takt Plan (with takt of one day)

### APPROACH TO DATA COLLECTION AND ANALYSIS

Data was pulled from Weekly Work Plans (WWPs) for three of the five buildings in the case study. Since takt planning was implemented halfway through the construction process, data only exists for part of the project, however due to the size of the project, extensive data was collected on takt plan failures. Using the WWPs, they applied continuous production control by marking every failure in the takt plan and assigning a reason for the failure. Through observation of common causes of takt plan failure, the flow managers identified sixteen causes for failures within the takt plan and each failure was placed in one of those categories. The WWPs were available for data collection and analysis for half of Building 3, and all of Building 5 and Building 6. Six months of WWPs were available for data collection and analysis for Building 3 whereas Building 5 and Building 6 both had over one year's worth of WWPs to pull from. Each failure in the takt plan was gathered from the WWPs and then compared with the FMEA framework outlined by Lehtovaara et al. (2022) with the goal of determining whether the proposed FMEA framework describes all documented causes for failure in the case study takt plan. Despite unequal data for each building, sufficient data was collected to determine the trends of the data. The number of takt plan failures for each failure identified in the case study was summed based on the failure category as well as the total number of failures for the building. Trends in the data are identified and possible explanations for the trends are discussed, such as the impact of a learning period after the implementation of a takt plan (on both planning and production sides).

## FINDINGS AND DISCUSSION

### DATA AND ANALYSIS

For each week in the WWPs, failures in the takt plan were identified by the superintendents, along with their associated reason for failure. Takt plan failures were only identified when the task would not finish on time. Therefore, the number of failures in the takt plan was not heavily impacted by the project having a takt time of one day. During data analysis both the task that didn't follow the takt plan and their reason for failure was pulled from the WWPs. Then the failures (called variances in the case study WWPs) were organized into the failure categories outlined in the FMEA-takt plan framework proposed by Lehtovaara et al. (2022). In the case study project, the flow managers identified sixteen types of failures that occurred in the takt plan. Notably, the failures include both administrative failures that impact construction tasks such as submittals, trade failures such as failed inspections, and logistical failures such as missing materials and equipment. The identified failures and number of each failure for Building 3 are shown in Table 1. Table 1 also correlates each failure identified in the case study to a FMEA takt plan failure.

An additional FMEA takt plan failure was added, titled 'other', that contains failures identified in the case study that don't correlate to any of the three FMEA takt plan failures. This category includes takt plan failures due to weather, unforeseen conditions, COVID, and unknown reasons (i.e., failures that are outside the control of a takt plan or uncontrollable in nature). This last type of failure was added by the researcher to describe the failures marked in the WWPs for which no distinction of reason for takt plan failure was given. Any number with an asterisk next to it (*) indicates that failure in the case study could fall into more than one FMEA takt plan failure category. Four of the case study failures fit this description: client change (it is assigned to wagon handoff but could be in the 'other' category because it is not directly part of the scheduled takt plan), submittals (same as client change), contracts (same as client change), and finished late (could result in a takt train failure). It was debated where the administrative tasks fit in the FMEA framework (client change, submittals, and contracts), however they were ultimately placed under wagon handoff because the takt plan methodology can be applied to all project aspects, not just physical construction. Further investigation into how a takt plan may be applied to all aspects of a project would be worthwhile in order to better understand all the factors that make a takt plan successful.

Table 1: Building 3 FMEA and Failure Classification

| | Types of Failures | | | |
|---|---|---|---|---|
| **Variances** | **Wagon Content** | **Wagon Handoff** | **Takt Train** | **Other** |
| Client Change | - | 0* | - | - |
| Submittals | - | 0* | - | - |
| Arch/Eng/Design | - | - | 4 | - |
| Contracts | - | 0* | - | - |
| Materials Not Available | 42 | - | - | - |
| Equipment/Lift Not Available | 2 | - | - | - |
| Labor Not Available | 125 | - | - | - |
| Prior Work Not Complete - Others | - | 125 | - | - |
| Prior Work Not Complete - Self | 23 | - | - | - |
| Schedule/Coordination | - | - | 70 | - |
| Weather | - | - | - | 37 |
| Unforeseen Conditions | - | - | - | 16 |
| Finished Early | - | 26 | - | - |
| Finished Late | - | 9* | - | - |
| COVID | - | - | - | 0 |
| Unknown | - | - | - | 2 |
| Failed Inspection | - | 1 | - | - |
| **Totals for Each Failure Type** | **192** | **161** | **74** | **55** |

For Building 3, wagon content failures account for the largest reason for takt plan failure, with *Labor Not Available* being the largest addition to the wagon content failures. The case study had construction spanning over large portions of COVID-impacted time, and therefore during a time of labor shortage in the United States. A case study conducted in a different time or place likely would not have *Labor Not Available* as the largest wagon content failure. *Prior Work Not Complete – Others* ties with *Labor Not Available*, accounting for 125 takt plan failures; this type of failure falls under wagon handoff and demonstrates how unreliability is still prevalent in takt plans as well as the importance of continuous improvement in takt planning.

Building 5 (shown in Table 2) was analyzed in the same way, however, results were very different. Takt planning was applied to construction midway through the construction of Building 3, and only six months of data was collected for Building 3. Building 5 was the first building that used takt planning for its entire construction, resulting in a much high number of variances or failures marked in the WWPs. Building 5 had approximately 2400 takt plan failures with 1/3 of them lacking a reason for failure (*Unknown*). This can be due to a variety of reasons, such as a lack of awareness of how to use the WWPs and the takt planning system and/or a lack of dedication on part of the superintendents to the takt plan. Therefore, the ‘other’ FMEA failure category is responsible for the greatest number of failures in the takt plan for Building 5. However, the second and third most common reasons for takt plan failure are *Labor Not*

*Available* and *Prior Work Not Complete – Others*, respectively. Building 3 was not unique in having a high percentage of takt plan failures due to *Labor Not Available* and *Prior Work Not Complete – Others*.

Table 2: Building 5 FMEA and Failure Classification

| | Types of Failures | | | |
|---|---|---|---|---|
| **Variances** | **Wagon Content** | **Wagon Handoff** | **Takt Train** | **Other** |
| Client Change | - | 14* | - | - |
| Submittals | - | 4* | - | - |
| Arch/Eng/Design | - | - | 26 | - |
| Contracts | - | 8* | - | - |
| Materials Not Available | 122 | - | - | - |
| Equipment/Lift Not Available | 19 | - | - | - |
| Labor Not Available | 363 | - | - | - |
| Prior Work Not Complete - Others | - | 313 | - | - |
| Prior Work Not Complete - Self | 68 | - | - | - |
| Schedule/Coordination | - | - | 131 | - |
| Weather | - | - | - | 141 |
| Unforeseen Conditions | - | - | - | 200 |
| Finished Early | - | 56 | - | - |
| Finished Late | - | 118* | - | - |
| COVID | - | - | - | 22 |
| Unknown | - | - | - | 851 |
| Failed Inspection | - | 35 | - | - |
| **Totals for Each Failure Type** | **572** | **548** | **157** | **1214** |

Analysis of data from Building 6 (Table 3) shows similar results with *Prior Work Not Complete - Others* as the top reason for takt plan failure and *Labor Not Available* as the second most prevalent reason for failure. For Building 6, the FMEA category that accounts for the highest number of takt plan failures is 'other' due to the large amounts of *Unknown* failures. However, the number of failures identified as *Unknown* decreased dramatically between Building 5 and Building 6. This shows the learning associated with the implementation of takt plan and reflects their efforts to use production control (Seppanen et al., 2004). Another difference from Building 5 is that the second highest FMEA failure category was wagon handoff as opposed to wagon content. This also shows learning on the part of the flow managers since they were able to better supply the materials necessary for construction. This is possibly due to outside factors, however for Building 6, failures due to wagon content errors is significantly less that failures due to wagon handoff.

Table 3: Building 6 FMEA and Failure Classification

| | Types of Failures | | | |
|---|---|---|---|---|
| **Variances** | **Wagon Content** | **Wagon Handoff** | **Takt Train** | **Other** |
| Client Change | - | 11* | - | - |
| Submittals | - | 2* | - | - |
| Arch/Eng/Design | - | - | 22 | - |
| Contracts | - | 5* | - | - |
| Materials Not Available | 69 | - | - | - |
| Equipment/Lift Not Available | 20 | - | - | - |
| Labor Not Available | 222 | - | - | - |
| Prior Work Not Complete - Others | - | 351 | - | - |
| Prior Work Not Complete - Self | 77 | - | - | - |
| Schedule/Coordination | - | - | 185 | - |
| Weather | - | - | - | 146 |
| Unforeseen Conditions | - | - | - | 167 |
| Finished Early | - | 86 | - | - |
| Finished Late | - | 100* | - | - |
| COVID | - | - | - | 10 |
| Unknown | - | - | - | 329 |
| Failed Inspection | - | 25 | - | - |
| **Totals for Each Failure Type** | **388** | **580** | **207** | **652** |

## DISCUSSION

The FMEA framework proved mostly effective in separating takt plan failures into correct categories. However, an additional ‘other’ category was necessary to account for conditions that cannot be controlled by takt planning, and to note the human error that occurred in documenting takt plan failures. This reflects what Binninger et al. (2019) found, that outside forces are major components in whether the takt plan follows the proposed schedule or not. Therefore, the FMEA framework for takt should be altered to account for these ‘other’ failures to improve effective application to takt projects in general.

The *Unknown* failures are important to note since they show that accurate documentation and reporting of variances from the schedule can influence an understanding of which failures are most prevalent. In addition, they show that without complete dedication on part of the superintendents to document failure information on the takt plan, FMEA may be harder to apply. Lehtovaara et al. (2020) list “social integration” as a key step to better takt planning implementation. To effectively use FMEA in conjunction with takt planning, the system must be socially integrated. In the case study, there were multiple superintendents and flow managers that worked to enable takt planning to be carried out on such a large project, yet, despite their best efforts, there was still significant human error that led to inadequate data collection. Therefore, it must be noted that successful takt plan application reflects whether the management teams and contractors are willing to put in the additional administrative work.

The amount of data and specifically the amount of clearly labeled takt plan failures across the three buildings shows learning on part of the project team. As they better learned to use the takt planning system and WWPs, more failures were identified, and more were recorded with an associated reason for failure. Building 3 has an artificially low number of failures as compared to the other buildings since the takt plan was not applied until halfway through construction. The project team also likely did not record all the variances that occurred in the takt plan because they were still learning how to work the new scheduling system. However, the volume of data enables some trends to be identified. The number of recorded failures jumped up dramatically with Building 5 due to the fact that they were more diligent in marking the variances from the schedule and that data was recorded for the entirety of the building's construction. A high number of *Unknown* failures was present reflecting the learning of the superintendents. Building 6 saw a decrease in both the number of *Unknown* takt plan failures and the total number of failures. The decrease in takt plan failures show continuous improvement, reflecting the goal of flow and lean construction (Koskela, 1992). Takt plans work but take production control to be effective. Between Buildings 5 and 6, the number of wagon content failures dropped significantly. The team worked to prevent wagon content failures as the project progressed. This resulted in a significant decrease in construction duration between the two buildings (Apgar et al., 2022). In fact, Apgar et al. (2022) found that there was approximately a 70% decrease in the total number of workdays required for roofing construction. However, the number of wagon handoff failures increased. An assumption may be made that if the project were to continue and more buildings were constructed and their failures analyzed, improvements would be made in wagon handoffs and the total number of takt plan failures would continue to drop.

Limitations to the study include the fact that the project was done on a case study, the study was done on a project not using the FMEA framework, and limited communication was available between the researchers and the project team. Although case studies are valuable to understand theory as it exists in practice, it is important to note that the results from the study are specific to the project. This project was a large scale, repetitive project that implemented takt planning halfway through. Other projects may have very different results due to size, project nature, and method for takt plan implementation. The case study project did not use the FMEA framework, so failures in the takt plan were classified according to the project flow team. It is important to note that since the FMEA framework wasn't used, the researchers were unable to analyze the full impacts of FMEA on a project. In a project where FMEA has been fully applied, continuous improvements are made as failures are identified to improve project performance over time. However, the purpose of the study was to determine whether the FMEA-takt plan framework addressed all the failures that exist in a takt plan. The project goal was achieved but the project must be understood in context. Limited communication prevented the researchers from understanding more about some of the failure categories designated by the lean innovation team on the job site. Using intuition and available resources on the WWPs, the researchers fit the project failures into the FMEA-takt plan failure categories as best as possible. Many of the failure categories given in the project, however, were self-explanatory or easy to infer context for due to notes in the WWPs. Therefore, despite limitations, the case study effectively increased an understanding of how failures exist in takt plans and how they might fit into a FMEA framework.

# CONCLUSIONS

The purpose of this paper was to serve as a case study to test the validity of the failure types identified by Lehtovaara et al. (2022) in their proposed FMEA-takt plan framework. Collected data and analysis demonstrate that although the framework works for most failures in a takt plan, another category should be added to account for the failures that are beyond the scope of the takt plan or outside of normal causes for failure within a takt plan. These include failures such as *COVID*, *Unforeseen Conditions*, and *Unknown* failures. Although possibly not true for every project, *Unknown* failures should be expected since not all failure may be documented correctly nor fit into a specific failure category. This is not to say the rest of the FMEA-takt plan framework is not applicable or that it could not be altered slightly to fit all types of failures that occur in a project with a takt plan. The purpose of the study was to determine whether the proposed failure categories might work for a real project. The study demonstrated the learning that is associated with takt plan implementation on a large scale, repetitive project. As the project team learns the takt plan production control method, takt plan failures decrease.

An additional insight the researchers gathered while conducting the study was that some takt plan failures result from administrative decisions. The researchers chose to sort those failures into wagon handoff failures. However, since administrative decisions exist above the scope of a takt plan, they could also fit into 'other' failures. This allowed for the insight that it may be valuable to apply takt planning to all processes that exist within a project, not just the construction process.

Further research should be done to follow the proposed FMEA-takt plan framework through the lifecycle of a project (Lehtovaara et al., 2022). Research should also be done on other projects to discover whether certain failures are more prevalent takt plans than others or if they are completely project dependent. Additionally, further research should be completed to understand the relationships between failures and whether seasons, trades, or areas in the world are more predisposed to a certain failure than another.

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