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HOW DOES *FLOW* IMPACT DATA CENTER ROOFING DURATIONS? A CASE STUDY

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ABSTRACT

Throughout the last few decades, a slow shift from the Critical Path Method to other, flow-focused scheduling methods has occurred in the industry. However, they have not yet been widely implemented by construction companies. This case study was conducted on a private data center project on a large site in which the project team has applied Takt time, pull planning, and location-based scheduling (i.e., Takt planning). The case study takes into consideration the roofing schedules for five buildings constructed over a span of three years and compares their total roofing task duration before and after the implementation of these techniques. The analysis has shown that a focus on flow and implementation of Takt planning on a large data center project decreases the overall duration of roofing construction tasks. This case study serves as a support for the transition from the traditional Critical Path Method to Takt planning or a flow-based approach since it has effectively decreased total roofing duration in this project.

KEYWORDS

Takt planning, location-based management (LBM), flow, pull planning.

INTRODUCTION

Scheduling using flow-focused methods isn't widespread in the construction industry. More commonly used is the Critical Path Method (CPM) created by Morgan R. Walker and James E. Kelley (1959). CPM was developed as a cost and resource optimization model and helps contractors focus on a common goal (Kelley & Walker, 1959). CPM optimizes construction by listing critical tasks and the order in which they should be completed so as to decrease overall construction and to estimate total construction duration for the project. In practice this optimization model soon changed into a management and planning technique (Koskela et al., 2014). The schedules created by CPM must consist of optimal tasks for the method to be effective. Issues have arisen in its application since there was no verification that the tasks in the schedule were optimal, leading to CPM producing unpredictable results (Jaafari, 1984; Koskela et al., 2014).

Flow methods differ from CPM by focusing on the importance of the quality of the process as opposed to merely achieving deadlines (Sacks et al., 2017). Emphasizing the importance of the process results in improved reliability and decreases the likelihood that delays on one task will delay the entire project (Bertelsen et al., 2007). Flow methods also

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contrast activity-based methods for scheduling because they consider all activities and objects as interconnected (Kenley, 2004; Garcia-Lopez et al., 2019). From the idea of flow, first found in the manufacturing industry, comes pull planning, the Last Planner System®, location-based management systems, and Takt planning (Ballard, 2000; Frandson et al., 2013; Kenley, 2004; Kenley & Seppänen, 2020; Yassine et al., 2014). All prioritize recognition of the interconnectedness of activities with the goal of creating more reliable projects and improved scheduling in construction.

The purpose of this case study is to analyze the impact of flow scheduling on a large-scale repetitive project. This analysis provides support for the use of flow-based schedules using Takt time, pull planning, and location-based scheduling as a guide. Generally, in lean, these are called Takt planning schedules, but flow-based schedules or flow schedules will be used interchangeably with Takt planning in the paper since that was the title given to these schedules by the general contractor of the case study project. This research was approached with the hypothesis that using Takt planning would result in faster and more effective construction. Analysis of the roofing schedules of the data centers was completed through comparison of both start/completion dates and duration for the scheduled tasks before and after the implementation of Takt planning. The analysis supports the idea that an increased focus on flow resulted in an overall drop in duration for the completion of roofing tasks. The case study is unique in the sense that it is a large-scale repetitive project which spans several years and several buildings. The buildings that have been constructed for the project are almost identical. Therefore, a comparison between the schedules for the buildings is a valid method for analysis. Although the findings are unique to the case study project, this research and analysis has shown that the shift from CPM to Takt time, location-based scheduling, and use of pull planning can lead to shorter construction periods.

LITERATURE REVIEW

Traditional schedules focus on the ordering of critical tasks required to finish construction. Although these tasks are necessary, activity-based scheduling methods prevent maximum efficiency from being achieved. CPM is one such activity-based scheduling method. Yet, despite its failure to create maximum efficiency it has been called the “most important innovation in construction management in the 20th century” (Koskela et al., 2014). It received such high praise based on its apparent ability to bring order and focus to the construction industry. However, more recent studies suggest that CPM prevents maximum efficiency from being achieved and acts as a zero-sum game (Sacks & Harel, 2006). CPM often lends to each trade making decisions in their best interest instead of the best interest of the project meaning that some trades will get ahead while others are put at a great disadvantage. Activity-based scheduling methods such as CPM struggle to be applied to construction because each construction task is too big, resulting in unpredictability and unreliability (Kenley, 2004; Koskela et al., 2014). Unpredictability and unreliability are the problems that flow-focused methods seek to solve. As such, flow-focused methods have been researched and applied in attempt to find better ways to manage construction sites.

After manufacturing was revolutionized by the Toyota Production System, Koskela realized that several concepts could be applied to construction (1992). Shingo’s study on the Toyota Production System introduced two flows that work together to result in greater overall flow: operation flow and process flow (Shingo & Dillon, 1989). Although both operation flows and process flows are applicable to the construction industry, construction often emphasizes process flows (Sacks et al., 2017). There are two significant differences between construction and manufacturing that make flow difficult to apply. In construction the workers move around the project as it grows as opposed to having the project move to the workers (Tommelein et al., 1998; Kalsaas & Bolviken, 2010). Additionally, each project in construction is unique, making flow much more difficult to achieve (Bertelsen et al., 2007). These difficulties have led to both a slow transition away from CPM, and a large sum of research on how flow-based methods can be beneficial in construction.

In the construction industry, flow references any method that reduces variability and thus increases reliability (Tommelein et al., 1998). This often occurs by reorganizing resources so as to result in synchronized progress among all of the trades (Yassine et al., 2014; Tommelein, 2020). Building on the more generic ‘process flow’ presented by Shingo, Koskela classified seven specific flows that can help achieve overall flow in construction: labor, equipment, workspace, materials, precedence, information, and external flows (Shingo & Dillon, 1989; Koskela,1999). Other literature in construction builds on these seven flows or adds their own types of process flows to the list. However, there are two that are most heavily discussed and will be considered in depth: workflow and spatial flow.

Workflow refers to the flow of work within each trade and between each trade. When it comes to workflow, changing from a push planning method to a pull planning method can greatly increase the workflow in construction. Where push planning seeks to meet deadlines without regarding the feasibility of the work assigned, pull planning starts with the trades and asks what they can commit to accomplishing in a specific time period (Ballard, 2000; Khan & Tzortzopoulos, 2015). One example of a pull planning application is found in the Weekly Work Plans in Ballard’s Last Planner System® where the subcontractors meet each week and use pull planning to schedule what work will be done before they meet next (Ballard, 2000). Weekly Work Plans have shown an increase in Percent-Planned-Complete for each week, thus increasing workflow reliability (Khan & Tzortzopoulos, 2015). However, workflow in construction consists of more than just pull planning techniques.

Spatial flow is a second general ‘flow’ researched most likely due to the fact that space is one of the most valued resources in construction (Häringer et al., 2019). In fact, having multiple trades working in the same area reduces productivity for all, and having space where no work is being completed is a form of waste (Deschamps et al., 2015; Sacks et al., 2017; Binninger et al., 2019). Therefore, the space use on a construction site must be maximized. Location-based scheduling recognizes the importance of spatial flow in construction by treating space as a resource to be divided among the trades (Kenley, 2004). It differs from activity-based scheduling methods by assigning each trade a space in which to work as opposed to scheduling a task to be completed (Kenley, 2004). Maximizing spatial flow results in more trades working on the site at the same time and furthers the development of the project. As aforementioned, using these location-based techniques with Takt time allow for greater overall flow to be achieved (Kalsaas & Bolviken, 2010). Not only does spatial flow refer to the development of location-based scheduling, it also generally refers to the impact of the physical movement of workers and products on flow (Alves et al., 2000). Alves (2000) also states that spatial flows should be considered in order to minimize unnecessary movement and increase mobility between work sites. Thus, all trades, work assignments, and products should be considered and managed in a way that maximizes the utility of space and increases spatial flow.

Takt time planning is used to increase both workflow and spatial flow by maintaining continuous work in all areas of the construction site (Sacks et al., 2017). Takt time planning is a combination of pull planning, location-based scheduling, and Takt time. The first decision when implementing Takt time planning is to choose a Takt time, essentially a cycle time, chosen with consideration to the demand of the customer (Frandson et al., 2013). A Takt time determines what size of task each trade should complete in the specified time, and the amount of space they will occupy. Choosing an aggressive Takt time, such as one day as opposed to a Takt time of five days would result in smaller, more detailed tasks scheduled for each trade as well as the occupation of a much smaller area on the construction site (Chauhan et al., 2018). Therefore, Takt time planning works in conjunction with location-based scheduling in order to break up tasks to fit smaller workspaces. An optimized Takt time will result in the trades completing construction at a rate that matches the demand of the customer exactly (Hopp & Spearman, 2008). Breaking up the tasks to fit a Takt time creates a rhythm of work and ensures workflow reliability (Binninger et al., 2019). Takt planning also allows for early recognition of workflow issues (Frandson et al., 2013; Kujansuu et al., 2020). Furthermore, it leads to an increase in workflow due to use of capacity buffers instead of time or space buffers (Kujansuu et al., 2020; Tommelein, 2020). A capacity buffer means that a slower trade might make up work on days not scheduled or have another worker come in to help speed up the work (Yassine et al., 2014; Tommelein, 2020). On the other hand, trades that move quickly reduce their capacity to keep the Takt time. The research done on Takt time planning has proven its efficacy as a method for improving workflow and spatial flow.

Flow is challenged by both the prominence of CPM in the industry and the concept of resource efficiency. Flow maintains a customer-value focus whereas resource considerations value achieving the lowest production cost possible (Wernicke et al., 2017; Binninger et al., 2019). Also, maximizing resources through flow may lead to more waste in other areas, making it appear as a trade-off instead of an entirely beneficial system (Ebbs & Pasquire, 2018). Therefore, although flow may result in greater reliability and less variability, it can increase the cost of construction and may result in greater waste in other areas. The combination of these two downfalls to flow can lead to hesitance on the side of contractors to adopt it as a viable method for construction scheduling.

Starting with the Toyota Production System that revolutionized manufacturing, the concept of flow continues to be studied in depth. The construction industry has been able to apply this concept specifically through the development of pull planning, a greater awareness of spatial flow, and Takt planning. Although there are some challenges to flow, a shift to scheduling with an emphasis on flow continues to be supported by recent research findings. The case study detailed in this paper will serve as a specific example of the impact of changing from a traditional construction model to a model focused on flow.

METHODOLOGY

The research done used a case study methodology to discover the impact of the use of Pull planning, location-based scheduling, and Takt time on the duration of roofing task construction in a project. A case study methodology refers to the exploration of a concept in a removed manner. Instead of conducting experimental design research, the researcher collects data from a natural setting in order to arrive at a conclusion about their topic of interest (Crowe et al., 2011). Case studies are inherently valuable due to their ability to apply theoretical concepts to real-life situations and allow for a better understanding of complex topics (Crowe et al., 2011). A case study approach is a valid form of investigation for the topic of the paper since research was completed on the impact of newer scheduling methods in construction and was conducted on a topic of study over which the researcher could not control the outcome (Yin, 2013).

Despite its value as a methodology, case studies have distinct limitations. A notable limitation is that the results from case studies cannot be applied to all situations since they are case specific (Crowe et al., 2011). However, these limitations are overshadowed by the value they provide in growing an understanding of theoretical topics applied to real-life contexts.

The methodology within this case study combines empirical analysis with qualitative information from an on-site Lean Innovation Manager. Numerical data from various schedules were analyzed by tabulating information on start and end dates for each task as well as the duration of each task in the schedule. During analysis, two different types of schedules from the project were consulted: schedules developed using CPM in the early stages of the project (for all buildings 1-6) and schedules developed using flow-focused methods for buildings constructed in the later stages of the project (5-6). The quantitative results for the different schedules were compared and further analyzed to determine the impact of the flow-focused methods on roofing construction periods and durations. The second part of the methodology was an iterative process of discussion with the Lean Innovation Manager. Bi-weekly meetings were held to check the progress of the data analysis and verify the interpretation of the data. During discussions the current results were reviewed in conjunction with clarification on how the data was analyzed and what other data would be beneficial to investigate the impact of flow-focused scheduling.

Data collection and analysis occurred during the construction of the final part of the project and thus Weekly Work Plans were also consulted to verify the information and conclusions from the analysis.

FINDINGS AND DISCUSSION

FLOW METHODS IN THE CASE STUDY

In the case study, the general contractor changed their scheduling approach from CPM to flow methods. The implemented methods include Takt time, location-based scheduling, and pull planning. The project consisted of the construction of five large data centers. The first three buildings (1-3) were scheduled using CPM while flow scheduling was implemented during the construction of the final two buildings (5 & 6). All the buildings in the project are essentially identical and have the same floor plan. Data from schedules (both projected and as-built) include both CPM scheduling techniques and flow-focused scheduling techniques. The existence of two different types of schedules for the construction of essentially identical building in the same project allows for the impact of the flow schedules to be determined within the case study without any specific experimental design by the researcher.

The Lean Innovation team on the project decided to implement a Takt time of one day. This means that in the large buildings being constructed, the areas for construction would need to be broken into much smaller pieces and the tasks altered to fit the short Takt time. This change was reflected between the two schedules. The flow schedules include more area assignments for construction. For example, in the CPM schedules the roofing tasks are assigned to an Area (A-E) while the flow schedules are assigned to an Area (A-E) and a cardinal direction resulting in seven more construction zones for the low roof (the buildings have both a low roof and high roof). Some tasks were broken into smaller pieces resulting in more roofing tasks in the flow schedules. It is important to note that although there is a Takt of one day, it doesn't mean that every roofing task was completed in one day just that roofing was scheduled day-by-day in a highly detailed manner in order to maintain a rhythm. The flow schedules are included below but due to the confidential nature of the project, the CPM schedule is not.

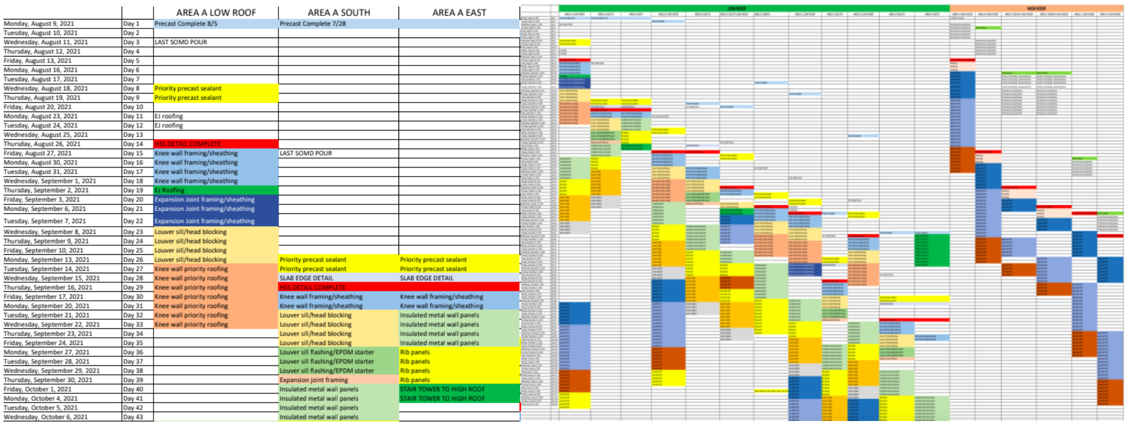

Figure 1: Flow Schedules (Takt Planning Chart)

In addition to splitting up the buildings into more construction zones, the Lean Innovation team addressed spatial flow by changing the order of the construction of the areas in the centers. Originally construction would start in Area E since it was the area that contained the most electrical work, then move outward to Area A and continue in alphabetical order from there. However, after the implementation of a flow-based system construction flowed through the areas in the order which the areas were located, going from Area A to Area B, Area E, then Area C and Area D. This simple change decreased the waste that occurs from unnecessary movement among and between the trades while moving from one Area to another. A map of the layout of the areas is shown in Figure 2.

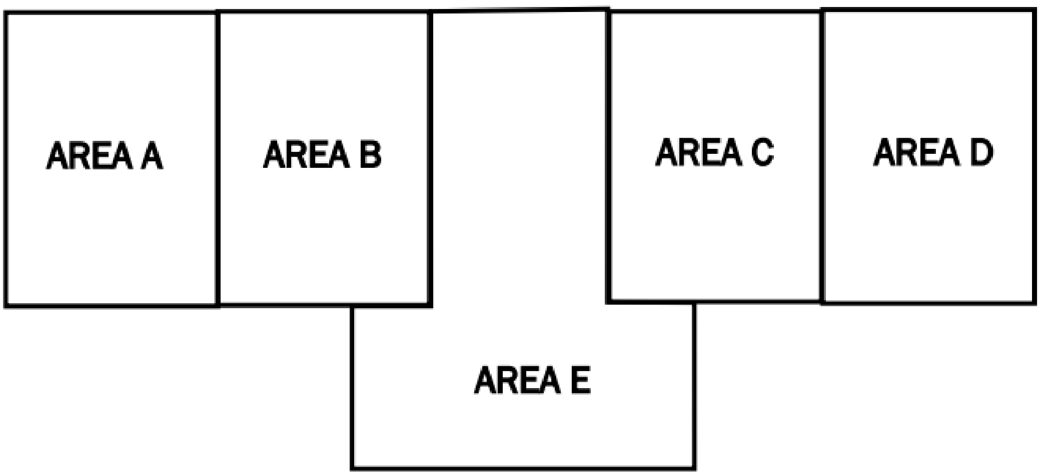

Figure 2: Building Layout with Areas

The schedules were also impacted by pull planning methods. Each week the contractors and subcontractors met and constructed a Weekly Work Plan (Ballard, 2000). The Weekly Work Plans (WWPs) reflected the Takt time of one day while also pull planning through the entire upcoming week. Although both the flow schedules and CPM schedules constructed for the project were created by superintendents with the job of creating and managing the schedules, the WWPs allowed for pull planning later in the project by updating the flow schedules to be as built and match current progress of the project. The flow schedules were updated to match current progress and aided by the WWPs for future work to be done. All schedules analyzed were up to date, reflecting the current progress and duration of roofing tasks despite the ongoing construction.

The combination of these changes to scheduling methods led to the current flow schedules used for the project.

FINDINGS FROM ROOFING SCHEDULE DATA

The roofing schedules were tabulated and analyzed in order to determine the difference in construction time between CPM schedules and more flow schedules. Roofing schedules were chosen for analysis since the research team was able to get in contact with the project coordinator of the roofing schedules and it was confirmed that Takt planning had been fully implemented in the roofing tasks. The data gathered include the duration and the start and end work dates for each roofing task and the total duration and start and end work dates for all roofing to be completed (for all buildings 1-6). All CPM schedules and flow schedules created for the project were sent directly from the Lean Innovation Manager, including a live document with WWPs and as-built flow schedules. The data was analyzed by summing the total work days required to complete all roofing tasks with overlap (adding the duration for all roofing tasks together regardless of date start and end overlap between tasks), without overlap (the amount of calendar days in a 6-day work week from start to end of construction), and the total number of tasks for each schedule. The tasks were labelled with their respective Area (A-E) and cardinal direction (if applicable). The tabulated analysis, as shown in Figures 3 and 4, does not reflect the Takt time, merely the total number of days to complete each task in order to determine the impact that flow has on overall efficiency and duration for roofing.

F Task	F Start	F Finish	F Duration
Area A Tasks and Dates			
Area A Priority Precast Sealant Low Roof	8/18/21	8/19/21	2
Area A HSS Detail Complete Low Roof	8/26/21	8/26/21	1
Area A Exterior Knee Wall Framing/Sheathing Low Roof	8/27/21	9/1/21	4
Area A EJ Roofing Low Roof	9/2/21	9/2/21	1
Area A Expansion Joint Framing/Sheathing Low Roof	9/3/21	9/7/21	3
Area A Louver Sill/Head Blocking Low Roof	9/8/21	9/13/21	4
Area A Knee Wall Priority Roofing Low Roof	9/14/21	9/22/21	7
Area A Insulated Panels Low Roof	10/7/21	10/15/21	7
Area A Rib Panels Low Roof	10/18/21	10/22/21	5
Area A Louver Install Low Roof	10/25/21	11/3/21	8
Area A Louver Sealant Low Roof	11/4/21	11/9/21	4

Area E Tasks and Dates			
Area E Exterior Knee Wall Framing/Foam/Sheathin (Low Roof to PH) - South	11-9-21	11-10-21	2
Area E Louver Sill/Head Dtl/Blocking Low Roof - South	11-11-21	11-12-21	2
Area E MEP Curbs and Penetrations (Low Roof)	11-15-21	11-16-21	2
Area E Roofing Low Roof Phases 1-2 (Conc Deck) North	11-17-21	12-1-21	9
Area E Insulated Metal Wall Panels (IWP/Tape) Low Roof South	12-2-21	12-7-21	4
Area E Rib Panels Low Roof South	12-8-21	12-13-21	4
Area E Low Roof Phases 3-4	12-14-21	12-27-21	8
Area E Louvers and Sealant Low Roof South	3-28-22	4-12-22	12
Area E Exterior Knee Wall Framing/Foam/Sheathing (Low Roof to PH) North	11-11-21	11-16-21	4
Area E Louver Sill/Head Dtl/Blocking Low Roof - North	11-17-21	11-22-21	4
Area E Knee Wall Priority Roofing - Low Roof	11/23/21	12/3/21	7

Figure 3: Example(s) of Organization of Quantitative Data from Roofing Schedules

Area D High Roof Phase 4	1/13/20	1/20/20	6	
Area D High Roof Phase 4 Part 2	2/27/20	3/12/20	6	
Start to End Date (actual construction):	**1/14/19-7/7/20**	**Total Duration (original then actual? with and without overlap):**	**1567**	
			without overlap: ~458 days (six day work with w/ 5 holidays)	
# of Tasks:	96			

Figure 4: Example of Quantitative Methodology

After all the data for the roofing schedules were summarized, they were compared to one another through numerical summary in the form of a graph. Graphs were constructed in order to allow for visual recognition of a pattern that may exist between the duration of construction, the number of tasks in construction, and the type of scheduling method utilized (Figure 5). Additionally, for the last building, complete CPM schedules and flow schedules were analyzed and compared to account for the fact that other results may be due to differences between each building, despite their similarities. A general trend in the graphs shows that flow scheduling results in a shorter roofing construction period both with and without overlap in work days, and a greater number of tasks. The duration of some individual tasks increased in the transition to a flow-focused model. For example, the task 'Area D Low Roof Phase 2' increased in duration by two days when the schedules changed from CPM to flow schedules. However, the overall durations for roofing construction have decreased. In the graphs comparing all the buildings, flow schedule data was used only for Building 6 since a complete roofing flow schedule for Building 5 was unable to be acquired.

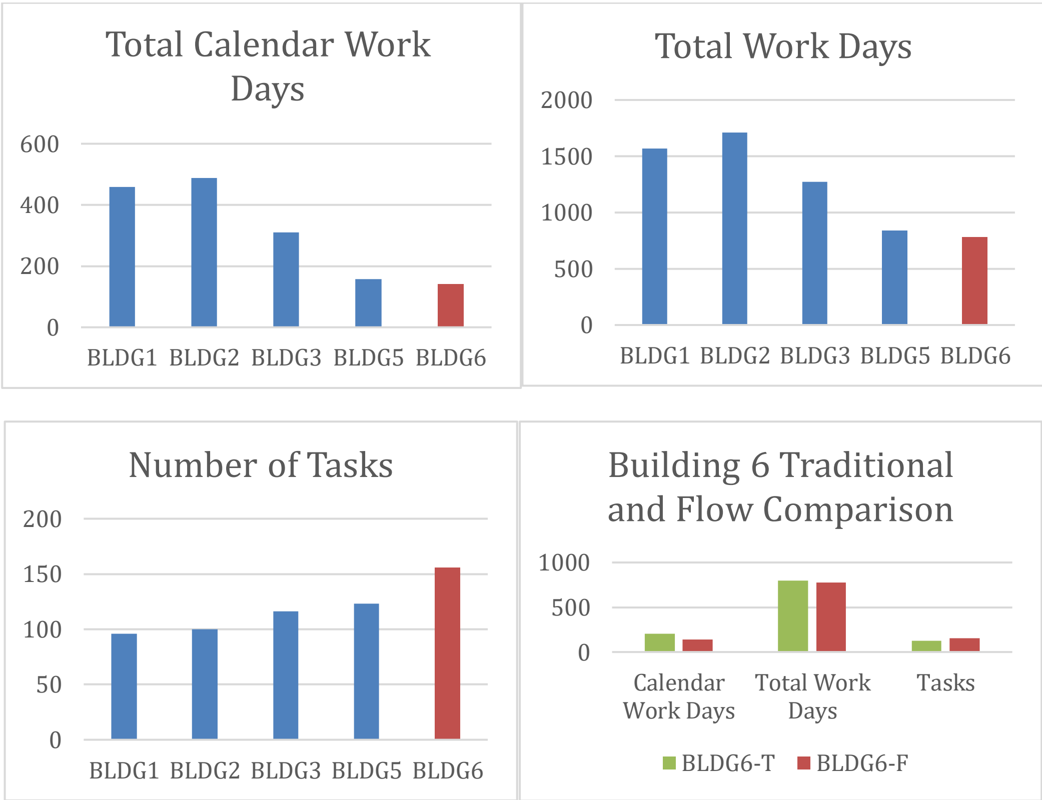

Figure 5: Graphs with Data Summary

The average for durations and number of tasks for CPM schedules were taken. This data was then compared to the scheduling data for the flow schedules of Building 6 in order to quantify the trends and overall impact that the flow schedules had on roofing construction duration. These calculations found that the total work days decreased by 72.9% in the flow schedules as compared to the average total work days for the other buildings. The total calendar work days decreased by over 200% on average. The number of tasks required for roofing increased on average by 43.4%. However, the data from Buildings 1 and 2 were skewed due to COVID-19 shutdowns in early 2020. Therefore, the same calculations were completed after removing the data from Buildings 1 and 2. These new calculations show that flow schedules resulted in an average decrease of 35.4% in total work days, a 64.8% decrease in calendar work days, and a 30.5% increase in total number of roofing tasks. Similar calculations between CPM schedules and flow schedules for Building 6 shows a 2.7% decrease in the total number of work days, a 42.9% decrease in the total calendar work days, and a 23.8% increase in the number of tasks for the roofing construction of the building.

QUALITATIVE DATA FINDINGS

An iterative process of unstructured interviews with the on-site Lean Innovation Manager revealed that the findings from the data accurately reflected the impact of implementing Takt time, location-based scheduling, and pull planning on the efficiency and quality of construction. This process also revealed that the general contractor had received positive feedback from subcontractors that have transitioned to flow methods, despite their original doubts. Therefore, the empirical summary of the case study is supported by qualitative data from regular interviews with an on-site manager that has been involved in the shift from more traditional scheduling techniques to flow scheduling techniques.

LIMITATIONS TO THE FINDINGS

There are some clear limitations to the findings. The method only looks at one area of construction as opposed to the entire construction project, acting as a case study within a case study. Therefore, the results only reflect whether roofing efficiency has been improved. Additionally, there only exists one complete flow schedule for the five buildings. Since there is only one complete data point from which to understand the impact of flow schedules on construction time, the change in duration could be a result of the learning curve of the construction crews. Additionally, the construction of two of the buildings was directly impacted by the COVID-19 shutdown in early 2020. The case study was also conducted during the construction of the last building, meaning that the full impact of the flow methods on roofing in the project has not yet been realized.

However, despite these limitations, steps were taken to ensure a valid analysis of the efficiency of the different methods for scheduling. For data analysis, roofing was chosen for analysis (instead of all tasks in the building) to allow for a greater understanding of the impact flow methods had on the tasks. It was also chosen because it was revealed through interviews that the roofing subcontractors had effectively implemented the flow techniques meaning that the change in roofing duration before and after the implementation of flow schedules would accurately demonstrate their impact on duration and efficiency. Both schedules were considered for Building 6 in order to show that the impacts of flow were not merely due to a learning curve. When asked about COVID-19, those working on the project responded that the durations of the tasks were correct, but the total completion time was not. Therefore, the different data summaries help to balance out the results from the impact of COVID-19 on the total number of days for the completion of the roofing for each building. Furthermore, when computing the same calculations after removing the data from Buildings 1 and 2, the results continue to show a significant drop in both work days and calendar work days as a result of flow scheduling. Lastly, the data analyzed was as-built even if not fully constructed. Therefore, despite ongoing construction, the data still reflects the impact of flow-focused scheduling methods on construction duration.

The limitations must be considered in the interpretation of the results of the case study but do not undermine the findings of the case study.

CONCLUSIONS

A case study was conducted on a private construction site to determine the impact of the transition to flow methods such as Takt time, pull planning, and location-based scheduling has on the duration of roofing construction. Empirical analysis and qualitative data collection have supported theories proposed that a shift to flow methods decreases construction duration greatly. In the case study, on average they led to a 72.9% decrease in total work days and over a 200% decrease in calendar work days required for total roof construction. The case study also shows that a transition from traditional scheduling to flow scheduling results in an increase in the number of tasks required to complete construction. Although the results are specific to the case study, they support a transition to flow-focused scheduling methods. Further research should be conducted to determine the impact of flow methods on other types of projects such as those of a much smaller size and on projects of a less repetitive nature in order to discover whether the findings to this research are unique in nature. To conduct this research, similar methods may be used but will be specific to their respective project.

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