TAKT TIME PLANNING AS A WORK STRUCTURING METHOD TO IMPROVE CONSTRUCTION WORK FLOW

By

Adam Frandson

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Committee in charge:

Professor Iris D. Tommelein, Chair
Professor William C. Ibbs
Professor Philip Kaminsky
Professor Dana Buntrock

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IV. GLOSSARY

Definitions marked with an asterisk (*) come from the P2SL Lean Construction Glossary (Tommelein, 2016).

Activity – A set of tasks for a trade that are combined in the schedule. If an activity has only one task in its set, then 'task' and 'activity' may be interchangeable. The tasks have different work contents. Figure IV – 1 describes this hierarchical relationship between activities, tasks, and work contents.

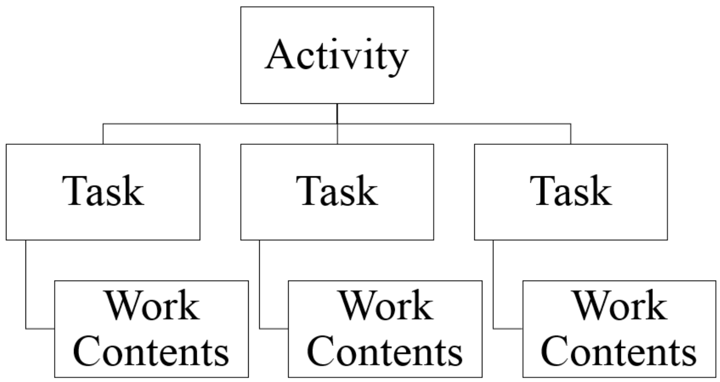

Figure IV - 1 – Hierarchical relationship between activities, tasks, and work contents

Buffer* – A mechanism for deadening the force of a concussion. See **Capacity buffer**, **Schedule buffer**, and **Time buffer**.

Capacity buffer – A way to accommodate variation in activity durations by reserving part of the total production capability of a crew or machine in a given time, i.e., underloading them. Two examples of capacity buffer are overtime work and planned idle time.

Clash – An intersection in virtual space between different objects inside a building information model.

Continuous flow process – A set of construction activities that work start-to-finish through multiple areas of work without any stop between the areas.

Linear work – A set of work that follows a linear path vertically or horizontally. Examples of linear work are road construction, skyscraper construction, and sewer construction.

Make Ready* - To take actions needed to remove constraints from tasks (assignments) in order to make them sound.

Milestone* – A point in time on the Master Schedule defining the end or beginning of a phase or contractually-required event.

Network relationship – The relationship between two activities in a schedule determining when they start and finish with respect to each other (e.g., start-to-start, start-to-finish, finish-to-start, finish-to-finish).

Productivity – The average output in a given unit of work per hour of work per person.

Pull planning – The scheduling of activities, starting from the end product, and working backward through the schedule. The purpose of pull planning is to identify clear handoffs, as opposed to working forward through a schedule where activities may be scheduled, but work for others is not released when needed.

Quantity of work – The total sum of work (typically in man-days) a team member needs to perform in a trade sequence in the physical space for a given area. The quantity of work could be considered for an entire floor, a designated zone, or an entire construction phase.

Repetitive work – A construction activity performed in multiple areas that is similar or identical in work density and task detail.

Reverse Phase Schedule (RPS)* – One level in the Last Planner System when a phase is separated out from the master plan, and people responsible for the work in that phase jointly develop the plan. People in a "design phase" may include engineers, architects, owners, designers; perhaps also permitting agencies. People in a "construction phase" may include designers, the general contractor and specialty contractors; perhaps also inspectors and commissioning agents.

The team starts at the end of the phase (the customer) and pulls (works backward) to determine (1) what aspect of work will deliver the hand off(s) needed by this customer (identifying the requirements to declare a chunk of work complete) and (2) the inputs, directives, and resources needed to perform the chunk(s).

The latter, in turn, become the customers, and the pulling is repeated until the entire phase is broken down into a network of work chunks. Work chunks specified by their outputs (I give) and needs (I get) may be written down on sticky notes (color-coded by performer) and pasted on a wall.

The chunks are then rearranged based on the start and end time of the phase, the durations negotiated to complete each chunk of work, allocation of slack where needed, and work structuring to achieve work flow.

Rough install – Also known as "Rough-in." Installation of a component in a building including all of the associated tasks until the task is finished. Example: Rough install of duct work would include everything related to installing the duct up until setting the register, start-up, air balancing, and testing.

Schedule buffer – A way to accommodate variation in activity durations by using workable backlog. Workable backlog is work that needs to be done, but is not on the critical path of the Master Schedule, and can be used to increase utilization of crews when planned work is not ready to start.

System – "Any collection of interdependent and interactive elements which act together in a mutual effort to achieve some (usually specifiable) goal" (Mihram, 1976).

Takt time* – Takt time is the unit of time within which a product must be produced (supply rate) to match the rate at which that product is needed (demand rate).

Takt time planning (TTP) – A work structuring method that aligns the production rates of trades by pacing work through a set of zones in a set sequence to create continuous workflow, reliable handoffs, and an opportunity to continuously improve the production system.

Task – An action taken by an individual or crew involving the installation of a component. The action could be a precursor to a construction activity (e.g., handling or ordering the component), installing the component, or follow the installation of the component (testing the installation, calling an inspection, etc.).

Time buffer – A way to accommodate variation in activity durations by planning extra time between the starts and finishes of activities.

Work contents – The specific components, including information, involved with a specific task.

Work density – The spatial distribution of installation hours required to complete work in an area as a function of the work contents, work methods, and crew size. The work density may be considered for a single trade or collection of trades in a specific zone or area.

Work structuring* – Process of breaking work into pieces, where the pieces will likely be different from one production unit to the next, to promote flow and throughput. Work structuring answers the following questions (Ballard, 1999, Tsao et al., 2004):

In what units will work be assigned to groups of workers?

How will work be sequenced?

How will work be released from one group of workers to the next?

Will consecutive groups of workers execute work in a continuous flow process, or will their work be decoupled?

Where will decoupling buffers be needed, and how should they be sized?

When will different units of work be done?

Work structuring is a dynamic process to be re-evaluated in the course of a project. At the project onset, work structuring deals with designing the overall system. As the project progresses, work structuring becomes more focused to guide the design and execution of interacting pieces of impending work.

Workable Backlog – See scheduling buffer.

Zone* – In Takt time planning, a delimited space where one production unit gets scheduled to complete their work within the Takt time. May also be known as a “Production area” or “Takt area”.

V. ABSTRACT

Work structuring is critical to project production system design because it helps to define who is doing what work, when, what the handoffs are, how they are doing the work, how long it will take, which buffers are required, and what construction work should flow continuously without time buffers. Takt time planning is a work structuring method that aims to achieve the lean principle of continuous flow. Successful Takt time planning on a construction site results in trades working on activities at the same rate to release work areas at standardized times. Current planning practices in construction fail to account for continuous flow for trade activities. This phenomenon has several causes: complexity of design, focusing on productivity maximization, contracting methods, lack of production system design, lack of resources, lack of a method to follow, and tradition.

The objective of this research is to develop a method for Takt time planning and improve understanding of work structuring for all construction phases in repetitive and non-repetitive construction. To meet the objective, the research will focus on non-repetitive interior construction because if a method of Takt time planning is effective there, it follows that the method can also work for construction phases in which the work is less complex and more repetitive. In order to show that the method is effective, the research must a) identify barriers to structuring work for continuous flow in interior construction, the most challenging phase, and how those barriers are overcome, and b) demonstrate the effectiveness of the method regarding project performance, time, cost, reliability, and resource utilization.

Continuous flow requires and releases workspace for trade activities at even intervals. An activity, defined as a combined set of smaller tasks, is repetitive in that it has the same installation duration for the same activity in every location. The actual work contents within the tasks themselves may be non-repetitive. The distribution in work contents is defined as the work density. This research focuses on the duration of each activity given a set of constraints: work method (e.g., offsite prefabrication versus on-site stick building), crew size, methods and tools for performing elemental tasks, etc.

This dissertation is structured as follows: an introduction to the topic and explanation of the intended contribution, a review of the relevant literature, and a description of the research method. The dissertation continues with a description of the instance of Takt time planning that motivated this research, followed by three case studies and a discrete event simulation to model key elements observed in the case studies. The research concludes with a proposed framework for Takt time planning, a discussion section, and conclusions with recommendations for future research.

This research uses design science (in particular, case study research) and simulation to accomplish the objective and answer the research questions. Each case study instantiates the Takt time planning method for different types of work, different phases of work, and with different team members to understand the current state of the project, test the method in different conditions, and advance production theory.

Case Study 1 examines the development and execution of a Takt time plan during interior construction of a 7,000 ft^2 urgent care unit at an existing hospital. The average percent planned complete (PPC) during the overhead MEP phase was 95% and the average PPC during the inwall MEP installation phase was 85%. Results from the overhead MEP phase of construction showed that structuring the work around continuous flow through small areas helped expose production problems and allowed the construction activities to improve upon the initial contract schedule

duration by 12 days on a 44-day schedule (27% improvement). The inwall MEP installation phase of construction improved upon the contract schedule duration by 8 days on a 37-day schedule (24% improvement). The project concluded with trade partners earning a bonus, in addition to their full contractual profit.

Case Study 2 used Takt time planning to build the interiors of a two-story, 26-bed 19,000 ft^2 psychiatric care facility. The project team used Takt time planning during two phases of the project with varying Takt times, spaces, team members, and work structuring constraints. The project finished with a 65% PPC and was delivered three months after the contractual completion milestone. Though the project did not complete on time, the project was a good case study for Takt time, as it provided valuable lessons on the method and application of Takt time that this dissertation discusses.

Case Study 3 focused on how Takt time developed in planning the production of the interior construction of a medical office building. The project is a two-story build out at an existing wood-framed, 14,000 ft^2 facility. The project was delivered with a GMP general contract and hard-bid subcontracts. This presented an opportunity to test Takt time planning in a new environment with a team unfamiliar with Lean Project Delivery practices. The project team used Takt time planning during three phases (overhead MEP rough-in, inwall MEP rough-in, and above ceiling close-up), completed successfully on time with an average PPC of 76%, and consumed 23% of its planned overtime budget, saving 20 days of Saturday work on a 144-day schedule.

The discrete event simulation demonstrates three work structuring methods: Takt time planning, a CPM schedule allowing early starts, and a location-based approach using time buffers. Each method has four trades working through four zones, in the same order, with finish-to-start network logic. The Takt time planning method resulted in faster completions with less variability in the completion time. If the daily indirect costs multiplied by the difference in completion times exceed the costs of the capacity buffer, then Takt time planning is the preferred method on cost and time. However, if the work is not being made ready, then the capacity buffer quickly becomes a cost sink to the project, and time buffers are preferred.

The contributions from achieving the research objective are fourfold. (1) A tested method of work structuring for continuous flow in interior construction, called Takt time planning. The method requires a paradigm shift from scheduling with 100% utilization of crews with buffers in time, to using capacity buffers to accommodate variation and produce reliable, timely handoffs. (2) Contributions to knowledge on the challenges of designing continuous flow into interior construction. (3) A simulation providing new insight into the trade-offs of using capacity buffers versus time buffers in work structuring on the overall project cost. (4) Questions for future research for Takt time planning in practice and for simulation.

CHAPTER 1 INTRODUCTION

1.1 CURRENT PRACTICE

Flow is vital to all production systems. Flow enables problems to surface, provides a clear understanding of where a bottleneck exists in a system, and clarifies the pace at which all activities need to produce. Buffers in time, capacity, or inventory are used so a production system does not grind to a halt when every problem occurs. However, creating continuous flow during a construction is challenging for many reasons. The required pace (e.g., the demand rate) is not always clear, workers move around the work, different types of work flow in different directions horizontally and vertically, network relationships between activities vary, the work contents vary, communicating a plan across multiple organizations is difficult, and construction practice needs methods for applying the principle of continuous flow in a project's production system (Birrell, 1980). In addition, there is little communication between the general contractor and upstream designers and detailers regarding any production strategy (Sacks et al., 2014). As a result, BIM clashes are often solved locally, as no global strategy exists, and models are built to be "clash free" and constructible. Often, design is incomplete when construction starts (Rosenfeld, 2014). Since the industry can barely manage to design for constructability (i.e., design a project that is feasible to build), designing for production (i.e., design to an overall production strategy to promote flow) is an aggressive goal.

Although there are challenges to applying continuous flow in construction, foundation and vertical construction work phases typically follow a pace for activities in the sequence, so the speed of steel erection or frequency of concrete pours primarily drive the schedule. However, interior work activities may follow any number of sequences at a variety of production rates, so a pace is much harder to identify.

Current practice schedules and executes interior work in a top-down sequence following a work breakdown structure and assumes full utilization of the crews. Activities are scheduled such that the people performing the work are used at full capacity, and variations from the schedule are buffered with time. The time buffering occurs when a scheduler assigns extra time for a crew to complete an activity, but also understands that the crew will move on to another activity immediately after completing the activity. The size of the time buffer and how the buffer is allocated vary, but the purpose of the buffer is to create a more reliable schedule. This does not mean that there is no hidden capacity buffer in the production system, only that it is not identified as such. The hidden buffer is generated by uncertainty in the future work (including the working environment), and resides within the subcontractor's internal production system. The subcontractors aim to locally optimize for themselves by maintaining efficient crews used at a maximum utility (i.e., assume full crew utilization). General contractors will enable this work structure to take place, with the assumption that locally optimizing every part can produce the best project overall.

This results in schedules comprised of varying activity durations, and crews moving at different speeds through the building because of the variation in installation times for different components, the total quantity of components to install by trade, and the location of component installation in space. Thus, some space on the floor may be more or less dense for one trade contractor, some trade contractors may require more or less time to install work, and there may be more or less work to install for different trade contractors. Some spaces may also be waiting for workers, while others are stacked with trade contractors working concurrently. Finally, during execution, crews maintain maximum utilization with the objective to complete their activities for the week and more if possible. However, is this approach to variability beneficial to the project as a whole?

Related to the full utilization approach is the assumption that going faster than the committed activity duration benefits the project. However, due to the network relationship of activities and their differing logistics requirements, a project team often cannot reduce the overall schedule duration because the production system cannot take advantage of the faster activity durations (i.e., one trade produces faster, but the entire team needs to go faster in order to complete the project sooner). Because the production system cannot take advantage of the faster activity durations, there are overproduction and possible cost overruns of little to no benefit to the project.

Subcontractors aiming for full resource utilization consider several factors. How many craftspeople do they consistently employ across their portfolio of projects? What are the individual demands of the projects? What are the skills of the workers they employ? The company size will determine how the company staffs the project; thus, what is "optimal" for one subcontractor may be quite different for another subcontractor in the same trade. As individual projects in a subcontractor's portfolio fluctuate in demand for labor, the subcontractors allocate resources where they need them most. The contractual incentives on projects will be critical in determining this resource allocation.

Techniques like Line of Balance Scheduling help to maintain the continuous use of resources and counteract the varying activity durations. While the continuous use of resources can help with productivity and crew allocation problems described previously, the handoffs of work between trades (and consequently, the progression of the project) may be less reliable because the production system is not structured to absorb variation in work release (i.e., when activities finish) with anything other than time.

Current practice may use the Last Planner System to improve production planning and control. However, Reverse Phase Scheduling does not guarantee flow, only activity sequence. Manually scheduling continuous flow is a challenge for an individual crew while simultaneously establishing a trade sequence through multiple work areas with multiple people who will be pull planning with their own objectives in mind. In practice, obtaining flow takes several meetings to accomplish, and must be a unified team objective. As such, most pull planning practices do not create flow because the conditions - every trade working at the same rate through the same areas in the same sequence - are not typically present.

The unpredictability of construction schedules, including when a project starts, also makes matching people to projects a considerable problem (Rittel and Webber 1973) for management staffing as well. As a result, construction projects are chronically understaffed in the first phases of construction, creating problems and missing an opportunity to start projects off correctly. Understaffing projects also creates a problem when more capacity is required to solve problems that could have been solved earlier with fewer resources. Furthermore, the uncertainty in people matching also prevents trade partners from committing foremen to projects in preconstruction, which can prevent accurate detailed production planning.

There is another problem in current practice within companies between project managers and their foremen. The burden of a crew's productivity is ultimately shifted from the project manager or area superintendent to the foremen (and then to the crew members), even though their productivity target may have been imposed on them. The internal problem can often shift to the production team at large. Even on projects using contractual agreements that incentivize shared risks and rewards, trade partners may be pushed for better productivity by project managers, and will show this frustration in planning meetings. Consequently, shifting the burden of high productivity from the trade partner to the team as a whole or general contractor would likely alleviate pressure on the foreman. The shift would also improve the production planning environment at difficult times when the team needs to solve problems together, rather than treating the problem as if it were an issue with a single trade partner.

If early planning failed to account for continuous flow, in order to accurately identify the correct trade sequence, and/or to create a schedule that considered site logistics, it will be the superintendent's responsibility to create the production system with whatever means are available. In some cases, this is in fact the starting execution strategy: have a good superintendent who can manage these problems on their own. Clearly, the industry can do better to create continuous flow.

1.2 Problem Statement

Production systems should aim for continuous flow; it benefits production systems because work in process is minimized, problems within the system can be identified and eliminated (rather than hidden), and the system is balanced to demand. The research problem is that current work structuring in construction fails to account for continuous flow for trade activities. As discussed in 1.1, this phenomenon has several contributing factors that make it difficult to create a schedule with continuous flow: complexity of design that may prioritize designing for constructability over designing for production, contracting methods that incentivize local optimization, lack of design of the production system, lack of resources, lack of a method, and tradition ("we have always done it this way").

1.3 Research Scope

The proposed scope is to address the research problem of the lack of a method to produce continuous flow in construction, and test a new method of work structuring, Takt time planning, in non-repetitive interior construction. This research tested Takt time planning on three case studies and used simulation to better understand how the method differs from other types of work structuring. Each case study focused on the build out of interiors on healthcare projects, primarily the MEP systems and rough carpentry. The physical construction is the focus of the case studies; however, this research also describes how Takt time planning affected and was affected by upstream flows from design and material procurement.

1.4 Significance

This research is significant for practice and theory. Reducing project risk of cost and schedule over runs is a continuous endeavor in project management; thus, if Takt time planning reduces that risk, it will be helpful to the industry.

A paradigm shift in scheduling practice is required for Takt time planning to be effectively incorporated into industry practice. The current paradigm aims to utilize crew capacities at 100% and control scheduled activities to maintain it, regardless of the cost to overall predictability and reliability of the production system. Takt time planning uses underloaded crews to accommodate variation (e.g., variation in work contents, crews, weather, etc.) and handoff zones reliably, creating a predictable environment to look ahead and align supply chains supporting the project. The idea of underloading in construction is not new, but the method of Takt time planning is (Ballard, 1998; Howell et al., 2001; Court, 2009).

Figure 1-1 illustrates the Kingman formula (1961). In the figure and from queueing theory, in a single server queue, cycle times increase when utilization and variation increase (in arrival and service times). Consequently, the traditional construction management attempt to buffer variation in arrivals and field installation durations with time buffers is destined to fail. Capacity buffers are needed in order to achieve reliable handoffs, without increasing project durations.

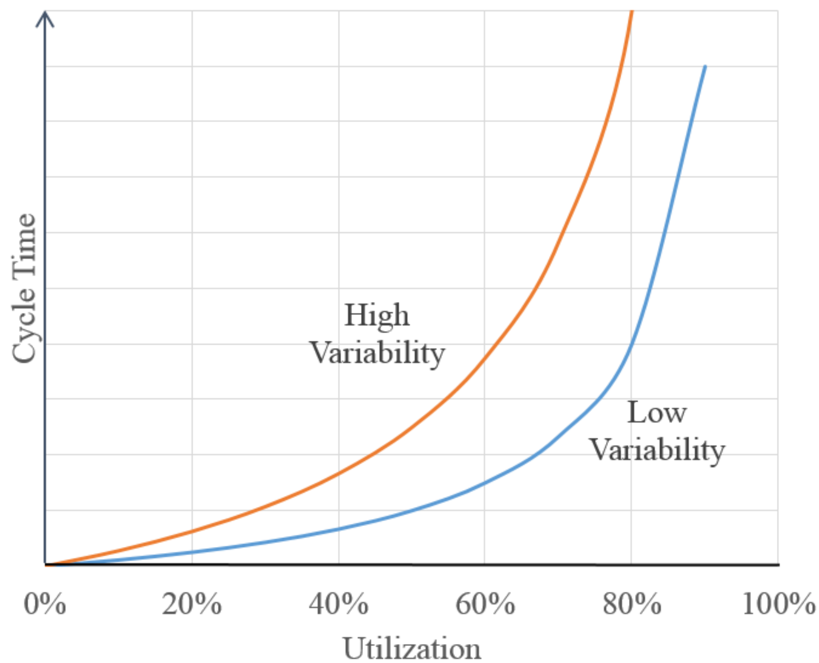

Figure 1-1 – Effect of variability on cycle times adapted from the Kingman formula

In practice, foremen schedule with some buffer in capacity, but what is not clear to anyone is how much, where the buffers are, the foremen's assumptions, and what alternatives are available. Evidence of the hidden buffers is obtainable from a conversation with a trusted foreman. One role of Takt time planning is to make this information known to the team so the production system can benefit as a whole.

This research is the first attempt to document and understand the benefits and challenges to implementing Takt time planning in interior construction. Interior construction can be characterized as unique production with low repetition in work contents. If Takt time planning can help project teams deliver value while reducing project risk, it will be welcomed by the industry and spread the use of Takt time planning. Furthermore, understanding how to implement Takt time planning in interior construction will also create the possibility for more in-depth research on the subject regarding capacity buffering, work density variance, the sociological impacts of Takt time planning on project teams, and an improved understanding between the commercial terms of a project and the implementation of Takt time planning.

1.5 RESEARCH OBJECTIVE

The objective of this research is to develop a method for Takt time planning and improve the understanding of work structuring for all construction phases in repetitive and non-repetitive construction. In order to meet the objective, the current research will focus on non-repetitive interior construction, because if a method for Takt time planning is effective there, it follows that the method can also work for construction phases in which the work is less complex and more repetitive. In order to show that the method is effective, the research must: a) identify barriers to structuring work for continuous flow in interior construction, the most challenging phase, and how those barriers are overcome; and b) demonstrate the effectiveness of the method regarding project performance--time, cost, reliability, and resource utilization.

1.6 RESEARCH QUESTIONS

1.6.1 QUESTION 1: WHAT DOES TAKT TIME PLANNING IN CONSTRUCTION LOOK LIKE?

The premise here is that interior building construction can incorporate continuous flow through production system design. Developing and testing a method of Takt time planning in interior building construction is important because it is a challenging project phase that can be generalized to other phases of building construction (i.e., if the method works in interior construction, then it will likely work elsewhere). While theory prescribes production system design as the means to achieve flow, little is known about the methods to achieve this. The specific method tested in this research is Takt time planning - an iterative, data-driven process that creates balanced work flow through careful design of the zones and their associated work densities.

1.6.1.1 Related Questions

What are the characteristics of flow in construction?

When should construction aim for flow?

Under what conditions is there a benefit to scheduling work while underloading?

Current practice in the construction industry typically schedules with time buffers if it buffers at all. Contractors schedule with the intent of 100% crew utilization, though foremen may opt to have extra workers on site to deal with some variation, or ask for a longer duration than the actual amount of time required to complete the activity. The shape of the curve in Figure 1-2 illustrates this buffering problem, with different letters representing different potential answers provided by a foreman on their completion time of an activity. A scheduler is not certain about what duration they are providing, or how to account (if at all) for the remaining variation. If the goal is to create a reliable schedule, then it is beneficial to schedule activities with "D" or "E" durations.

The process of Takt time planning can help reveal some of these hidden time and capacity buffers, with the intent of using them to create improved schedules. In Takt time planning, the goal is to root out variation and use capacity buffers so that the hand off is more reliable (Figure 1-3). Consequently, while buffering with capacity can mitigate unplanned and planned variation in work density, it is not an effective buffer for dealing with other causes of variation (e.g., material didn't arrive, work cannot continue without design, production for one trade is moving too fast, work stoppage). An example of planned variation in work density would come from a team identifying the installation hours required for different activities in different zones and understanding the variances between the zones. An example of unplanned variation would be actual differences in the installation hours required to complete the activities in the zones.

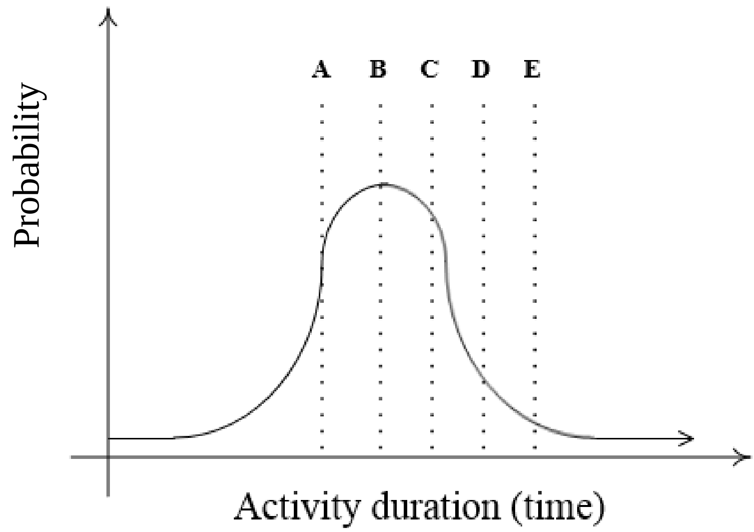

Figure 1-2 – Theoretical variation for a single activity duration

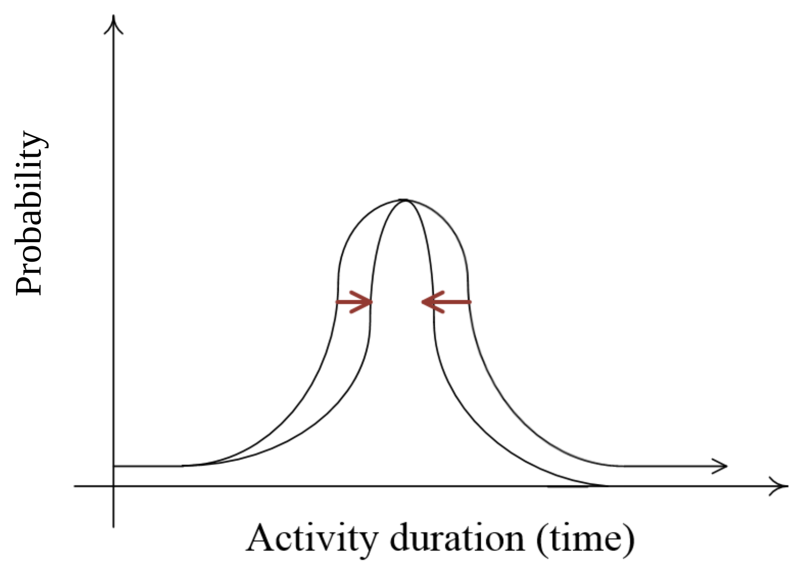

Figure 1-3 – Theoretical variation obtained through Takt time planning and using a capacity buffer

How can using Takt time planning as a work structuring method improve decision making for project execution? How are current work methods decided upon?

Work methods may be decided based on what is most economical, entails the least amount of risk, or what manpower is available. If a lean principle is to "optimize globally, not locally," then how does a production team know they are making the right decision when choosing between different work methods for an activity? Takt time aims to deliver a project quickly by improving the number of trade activities producing in a continuous sequence through work structuring. Does reaching this objective result in better decision making at a project level for work methods? In this circumstance, it would be better to make a decision that results in a lower total project cost, without sacrificing quality, safety, or schedule.

1.6.2 QUESTION 2: WHAT ARE THE BARRIERS TO DESIGNING CONTINUOUS WORKFLOW OF CONSTRUCTION ACTIVITIES?

To design for continuous flow, one must also understand the existing barriers because it is unlikely to get rid of the barriers completely. Barriers to designing continuous flow could come in several forms. There could be local barriers due to the work force and methods used, as well as social, temporal (too early or too late regarding the project start), economic, technological, or theoretical barriers (i.e., lack of a method or knowing how to design for flow).

1.6.2.1 Related Questions

What types of variation may be absorbed with capacity?

From observation, all activities have variation in their completion times deriving from a multitude of factors, including (Ogelsby et al., 1989):

1. varying work density on the project throughout different zones;
2. the skills of the person performing the work (i.e., if they are a carpenter, can they frame, hang, and lay out, or just perform one of those skills?);
3. different work methods;
4. varying quality requirements;
5. environmental conditions;
6. number of people performing the work;
7. familiarity with the work (i.e., the scope of work, processes on site, and construction plan);
8. (unknown) design issues;
9. material handling requirements;
10. function and availability of equipment;
11. variation in start time during the day; and

12. number of starts during the day (i.e., the person performing the work had to stop briefly to help someone else).

How reliable are Takt time plans? What happens if a Takt time plan is not reliable?

Understanding how a method fails is important for improving it. Takt time planning attempts to produce schedules with durations that will be met with certainty, because the small variation will be absorbed by a capacity buffer, as opposed to a time buffer. Thus, there is no variance around a mean, or 'percent likelihood' duration time that is scheduled. It is a set duration with '100% certainty' that the next activity will start. This works if the set durations are reliable. This could be measured via the percent plan complete metric used in the Last Planner System. As noted earlier in section 1.1, the Last Planner System focuses on reliable handoffs between trades. However, Takt time planning focuses on a reliable handoff within each trade (i.e., each trade needs to produce each zone within the given Takt time so the trade can flow), and if these handoffs are reliable, the problem of handing off work between trades is also achieved.

What are the consequences of designing a production system around different zone sizes?

Selecting a zone size is an important step of work structuring. During the case studies, it will be important to observe how the size affects the production system.

1.6.3 Question 3: What are the costs and benefits of using Takt time planning?

Does Takt time planning save the project money?

Case studies testing Takt time planning should begin to reveal if Takt time planning saves a project money overall. Takt time planning will incur costs to the project early on because downstream partners are moving upstream to provide design and schedule input. However, continuous flow of work among trade partners can have benefits downstream (e.g., less material delays, crews show up when needed, information is obtained in a timely manner, the plan is more widely understood and supported by the team), which should negate these initial costs. This would be an example of labor savings. Projects could also save money by reducing the overall project duration.

Does Takt time planning improve productivity?

In the current study, productivity is the average output in a given unit of work (e.g., linear feet of wall framing) per hour of work per person. The work is released at even intervals to enable a continuous use of resources; however, crew sizes are also used as a buffer to absorb variation in the work contents instead of the activity duration to ensure the timely handoff. However, if the handoffs are unreliable, attempting to follow the schedule may result in even more productivity loss due to lack of coordination, preparation, and trust in the schedule compared to a schedule using time buffers. Consequently, if a crew buffer is too great, then it may have a greater negative impact on crew productivity.

There is a related bootstrapping problem to productivity, as an estimator will often estimate the project before the zones are defined. Without buy-in from the team to define zones early in the project and estimate to them, the accurate measurement of production becomes a significant challenge to answering this question definitively. However, production literature provides some insight (Figure 1-4 and Figure 1-5) into how high crew densities (overmanning) and overtime may affect production; thus, it is still possible to compare the construction plans against these metrics. Assessing the productivity effects of a method or specific factor is a research endeavor of its own, and is not an objective of this research.

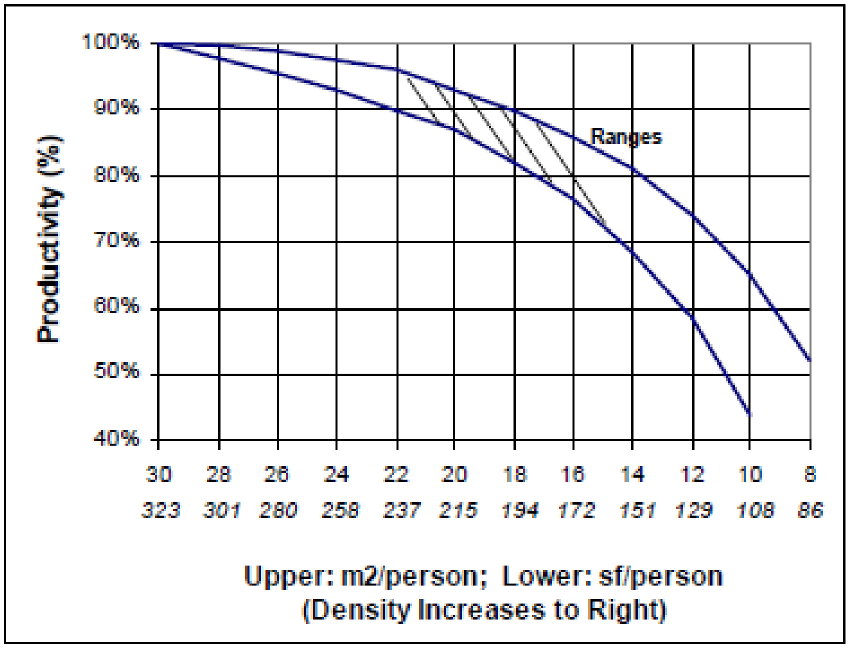

Figure 1-4 – Potential effects of crew density on productivity (adapted from Lee, 2007[1])

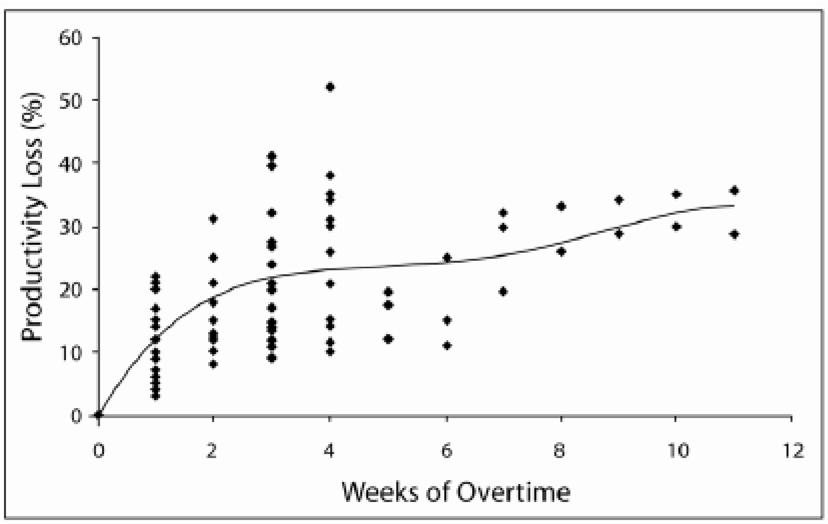

Figure 1-5 – Potential effects of overtime on productivity (adapted from Lee, 2007)

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1 Lee's figure was adapted from Smith (1987).

As a quick addendum to the productivity figures, Lee's dissertation was a comprehensive assessment of current productivity research. The effects of overtime are difficult to assess and there is no definitive conclusion, but the general trend is that prolonged use overtime on a project will result in productivity losses. It follows that if a project uses overtime sparingly, productivity losses will be minimal. In addition, if a project team schedules crew densities well above 320 ft^2/person, then it is an assumption backed by research that the productivity will not be lost due to high crew sizes.

1.7 DISSERTATION STRUCTURE

Chapter 1 outlines the research. It begins with the current practice and the research problem, then discusses the problem's significance. The chapter also covers the research objective, scope, and questions.

Chapter 2 reviews the relevant literature, beginning with a review of production theory and location-based planning. The chapter also expands upon line of balance scheduling in order to demonstrate some of the specific work flow problems created by activities moving at different rates. Then the chapter reviews the Last Planner System and Takt time planning.

Chapter 3 describes the research methods used in this dissertation to answer the research questions.

Chapter 4 describes the first instantiation of Takt time planning in interior construction in a non-repetitive environment, the lessons learned, and open questions for Takt time planning.

Chapter 5 presents the first case study on the Mills Urgent Care Center. The case study presents the following topics: research timeline, development of Takt time plans, results, and discussion.

Chapter 6 presents the second case study on a psychiatric expansion project. The research timeline, development of the Takt time plans, results, and discussion are covered.

Chapter 7 presents the third case study on PAMF Danville. The research timeline, development of Takt time plans, results, and discussion are included.

Chapter 8 simulates Takt time planning and other work structuring methods to illustrate the differences between the methods in a controlled environment.

Chapter 9 proposes a framework for Takt time planning based on the results and lessons learned from the case studies.

Chapter 10 answers the research questions using findings from the case studies and simulation. The chapter also discusses the reliability, validity, and limitations of the findings. The chapter concludes with a general discussion of other observations from the research.

Chapter 11 concludes the dissertation with closing thoughts, contributions to knowledge, and future research questions.

Chapter 12 provides the dissertation references.

Chapter 13 contains appendices information on referenced papers co-authored by the researcher and an expansion of the simulation figure.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter provides a background for the concepts related to Takt time planning, beginning with a review of current production theory and location-based planning. The chapter ends with a review of Takt time literature up to 2016, work structuring, and an explanation of the Last Planner System. The overall purpose of this chapter is to clearly identify the theoretical foundation for Takt time planning and identify gaps in the research.

2.2 PRODUCTION THEORY

In 2000, Koskela answered two research questions: (1) is it possible to formulate a theory of production, and (2) does such a theory add to our understanding and lead to improved performance when applied to construction? Koskela answered the first question by identifying three historical views of production focusing on the concepts of transformation, flow, and value. Koskela proposed that a combination of the three views is required in a theory of production. In addition, Koskela created a hierarchy for production theory in order to describe the relationship between concepts, principles, and methods (Figure 2-1). The hierarchy is pyramidal, with concepts at the top, principles at the second level, and methods at the bottom level. This hierarchy helps to answer his second research question. By identifying the theoretical concept, namely the Transformation/Flow/Value (TFV) view of production, research has a foundation for principles and methods that apply to the principles in construction.

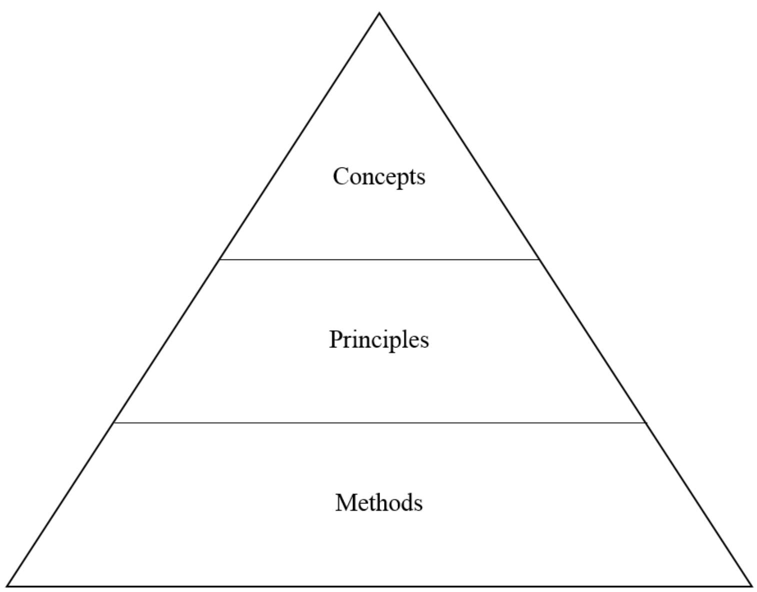


Figure 2-1 – Koskela's hierarchy for practical theories (Koskela, 2000)

2.2.1 Transformation Theory of Production

The transformation theory of production is the view that a production system can be broken down into its elementary operations consisting of inputs and outputs (Koskela, 2000). In Taylor's *Scientific Management*, these elementary operations are tasks (Taylor 1911). The objective in a transformation view of production is to optimize the tasks in order to optimize the whole system.

The transformation view of production dominates production system design in the United States, and influences practice. Initially, the transformation theory improved production systems. When moving from craft production to task specialization and a division of labor as described by Adam Smith in the *Wealth of Nations*, production increases (Smith, 1776). Division of labor and a movement from craft production also resulted from creating interchangeable parts (Hounshell, 1984). Nevertheless, production problems increase when demand becomes more variable, production systems grow in complexity (number of partners, design complexity, increased interconnectedness, etc.), and product mixes increase. Using a transformation view of production, the solution to this variation and uncertainty is to create push systems (i.e., a system that schedules releases of work), keep high inventories as a buffer, and try to manage long lead times (Koskela, 2000).

2.2.2 Flow Theory of Production

The flow view of production is fundamentally different from the transformation view, in that it identifies both process and operations in a production sequence (Shingo, 1988). Shigeo Shingo, a Japanese industrial engineer and Toyota Production System expert, writes, "Production is a network formed by intersecting axes of processes (the y-axis) and operations (the x-axis)." In the flow view, processes "refer to the flow of products from one worker to another, that is, the stages raw materials gradually move through to become finished products." Operations then, refer "to the discrete stage at which a worker may work on different products, i.e., a human temporal and spatial flow that consistently centers on the worker." An example of an operation would be a worker cutting sheet metal before it is fabricated into a piece of duct work. An example of a process would be the state of waiting for nine other sheets of metal to be cut before the cut piece of sheet metal moves to the next operation.

Shingo continues with the observation that from a transformation view, "the relationship between process and operation is typically defined as follows: processes are large units in analyzing production [and] operations are small units used in analyzing production." In the transformation view, there is no distinction between process and operations, other than the level of detail one observes in a process.

Using both processes and operations to describe a production system is helpful for two reasons. First, it helps to identify and eliminate activities that are non-value adding, defined as activities for which a customer is not willing to pay. These activities are considered waste. In the Toyota Production System, the eight forms of waste are: overproduction, waiting, transportation, over processing, excess inventory, unnecessary movement, defects, and unused employee creativity (Liker and Meier, 2006). Second, it reduces variation and product lead times to create flow.

One-piece flow is the ideal state of production in the Toyota Production System (Liker and Meier, 2006). A one-piece flow production system is a balanced production system in which each piece moves through different steps in the process with the same cycle time. Figure 2-2 is a diagram of one-piece flow. In this four-step operation, raw material enters the production system at Operation 1, and does not stop moving until it turns into a widget 20 minutes later. Because the material is constantly moving through each operation, one-piece flow is also an example of continuous flow.

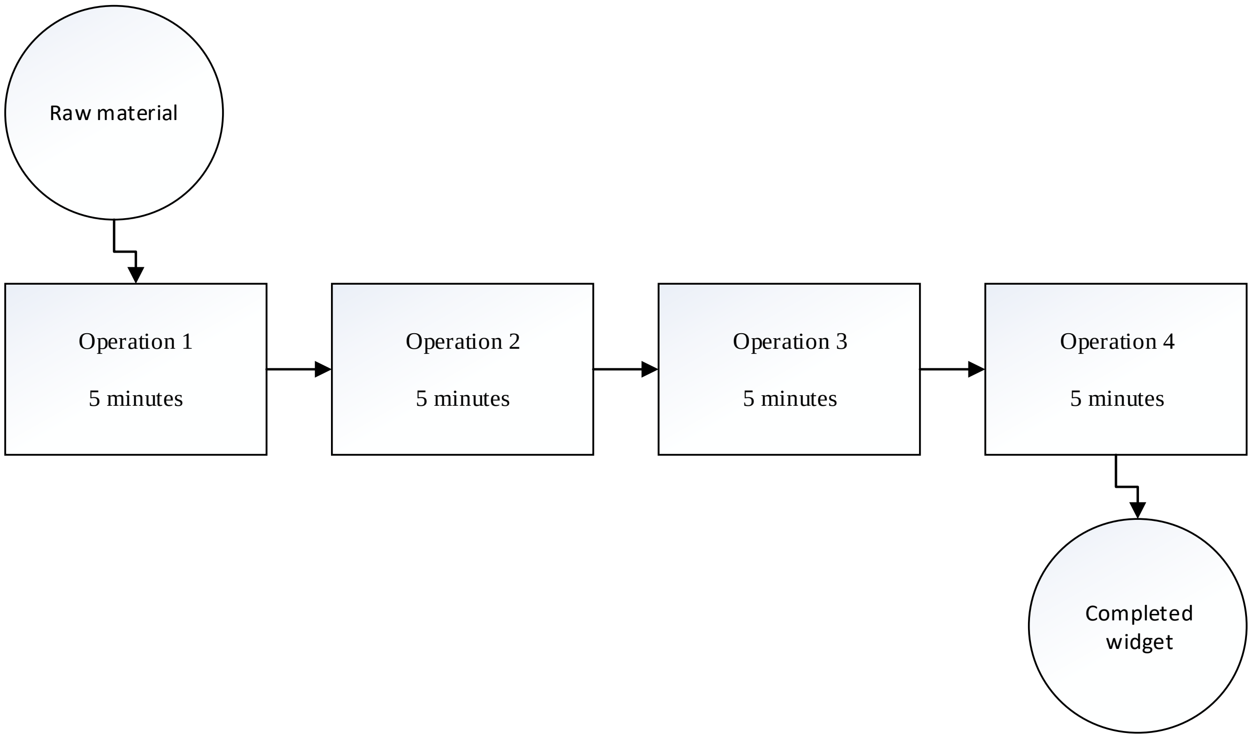


Figure 2-2 – One-piece flow example

While continuous flow reduces throughput time, it also provides the benefit of surfacing problems (Liker and Meier, 2006). Operations in a continuous flow sequence are all interconnected, so any cycle imbalance or production problem will affect the entire system and demand immediate correction. In the Toyota Production System, buffers are reduced over time as a continuous flow sequence becomes more stable to reveal more problems, and hence, opportunities for further improvement.

2.2.3 Value Generation Theory of Production

In a value view of production, customers are the focus because value can only be defined by them. In contrast to mass production, the value in a production system using value generation theory does not begin with transformation of material, but with the customer request as shown in Figure 2-3 (Koskela, 2000). Value generation theory also promotes working with suppliers to build in quality and acknowledge internal customers' needs when designing the production system (Liker and Meier, 2006).

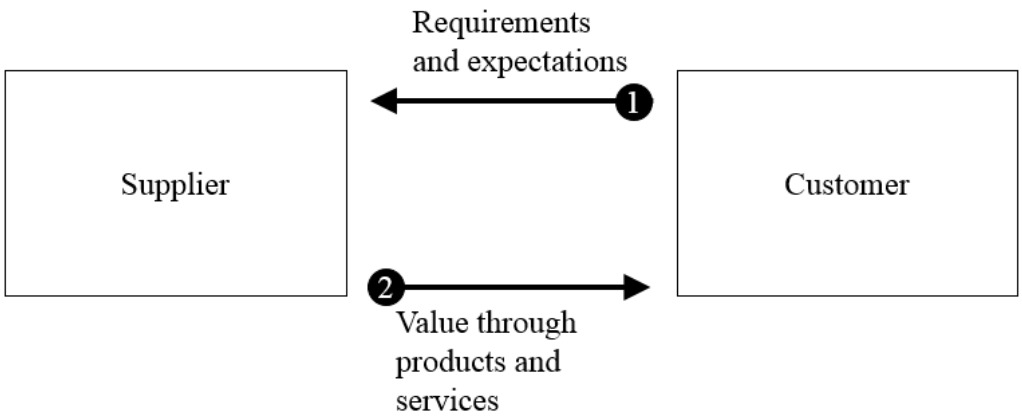


Figure 2-3 – Conceptual relationship between supplier and customer (adapted from Koskela, 2000)

Koskela (2000) listed five principles related to value generation.

1. Requirements capture – Accurately capturing the requirements of the customer is critical to understanding what to produce.
2. Requirement flowdown – It is vital to communicate those requirements internally and to downstream suppliers (flowdown) to ensure customer needs are met.
3. Comprehensiveness of requirements – Generating value not only in the product itself, but in its whole life cycle.
4. Capability of production subsystems – Each operation in the production system must be capable of meeting customer demand in quantity and quality.
5. Measurement of value – Verify that value was generated for the customer.

2.2.4 TFV Theory of Production

The TFV theory of production was the major contribution to knowledge from Koskela's (2000) dissertation. The theory states that all three perspectives (transformation, flow, and value) on production must be considered when designing a production system. The operations transform inputs to outputs, and may be divided into elementary tasks and completed efficiently. The production system must consider the flow of the system as a combination of operations and processes. Last, production management should create a design with a high quality solution based on a customer need. Failing to account for transformation, flow, or the value stream will result in more production problems or a product of inferior value relative to a system that considers all three concepts.

2.3 Location-based Planning

2.3.1 Introduction

Takt time planning is a form of planning that considers space; thus, it is closely related to past location-based planning research. This section presents location-based research divided into four topics related to Takt time planning: (1) Line of balance scheduling; (2) Location-based Management System (LBMS); (3) Space planning; and (4) Week-beat Scheduling.

Line of balance scheduling is a technique that represents space on the Y-axis and time on the X-axis. Research into Line of balance scheduling is divided into two categories: case study research and development, and research into optimization techniques via simulation and other algorithms. This section provides a review of both categories and uses Line of balance to illustrate work flow problems.

LBMS uses Line of balance techniques, but differs from it in that it is an actual method for planning and controlling a construction project, while Line of balance is just a schedule representation technique.

Space planning describes different efforts to include space in the schedule. 2D space modelling, 3D space modelling, 4D space modelling research, and different Space planning methods are included in Space planning.

Week-beat scheduling is a work structuring method that divides a project into zones with approximately one "week's worth" of work for an activity, paces work using a week as a Takt time, and uses a capacity buffer to deal with variation.

2.3.2 Line of Balance Scheduling

2.3.2.1 **Introduction**

Since the 1950s, construction scheduling techniques in the U.S. have primarily focused on network diagrams that reveal a critical path via the Critical Path Method (CPM). CPM techniques have been criticized for a lack of work continuity and scheduled resource idle time, both of which are not clearly represented and considered (Peer, 1974; Harris and Ioannou, 1998; Wang and Huang, 1998; Seppänen and Aalto, 2005; Vanhoucke, 2006; Long and Ohsato, 2009). Peer (1974) commented that CPM schedules "may comply with the needs of client," but "as experience has shown, the resulting schedule is of very limited use for site management, and the plans are quickly put aside before the work is really under way."

A Line of balance (LOB) schedule is a technique originally developed for industrial manufacturing, with the intent of creating work flow, or low resource idle time within the production line (Arditi and Albulak, 1986). The construction industry adopted this tool to maintain resource continuity. Line of balance schedules were first applied to construction projects with two types of repetition: linear repetition (roads, highways, etc.) and vertical repetition (high-rise, multi-story construction). The Line of balance schedule shows the activities and the crews completing the activities as lines on a 2D dimensional graph, with time on the X-axis and the space the activities move through on the Y-axis.

2.3.2.2 **History of Line of balance scheduling in construction**

Construction has used Line of balance scheduling for decades. In 1930, the Empire State Building's production system used Line of balance scheduling from design document completion (per-floor), to construction of the building (Willis and Friedman, 1998). Arditi and Albulak (1986) published one of the first case studies of Line of balance applied to pavement construction.

Line of balance is similar to other repetitive construction techniques, such as: vertical production method, linear scheduling method, velocity diagrams, even flow production, and repetitive scheduling method (Harmelink and Rowings, 1998; Duffy et al., 2011; Long and Ohsato, 2009; O'Brien, 1975; Wardell, 2003). The differences between the representations of the techniques are subtle, and stem from how each technique creates diagrams, and represents activities and crews. Some Line of balance schedules show activities as the primary line, and represent crew movements with horizontal lines moving upward with the activity (Figure 2-4). A linear schedule will show activities on the lines as well, but switches the time/space axes (Figure 2-5). Figure 2-6 and Figure 2-7 show how a flowline schedule combines the activity and crew on one line. Figure 2-4 and Figure 2-6 represent crews differently. Figure 2-4 depicts how the crews 'leap frog' through the units, while the flowline abstracts individual crew movement. The trade-off to this approach is less visual clutter, a critique of Line of balance schedules. For consistency, this research will adopt the Line of balance format, and refer to crews or activities on the drawn lines, as shown in Figure 2-6. From now on, if a schedule provides the activity and crew size in a flowline schedule, it will still be referred to as a Line of balance schedule.

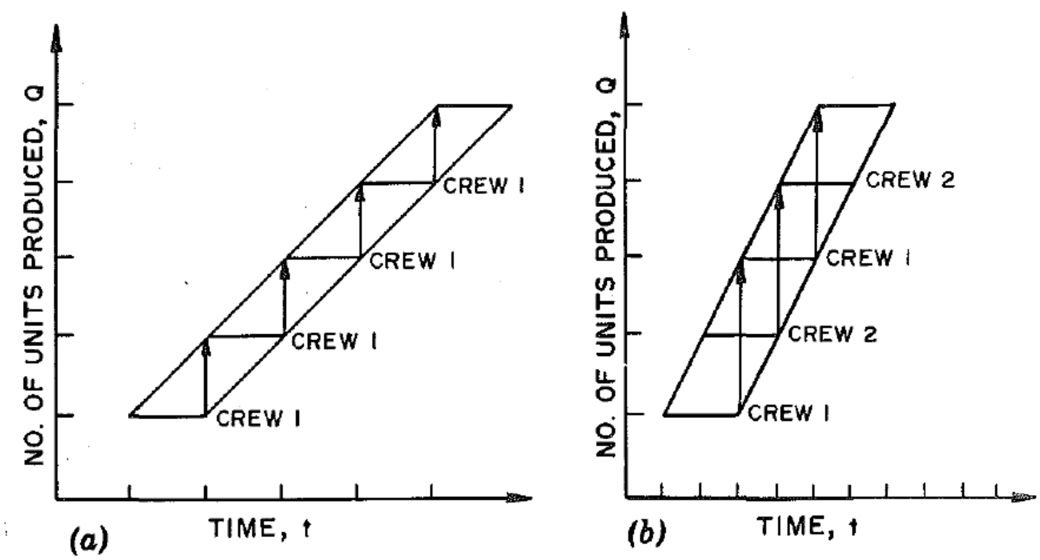


Figure 2-4 – Line of balance schedule example from Arditi and Albulak (1986)

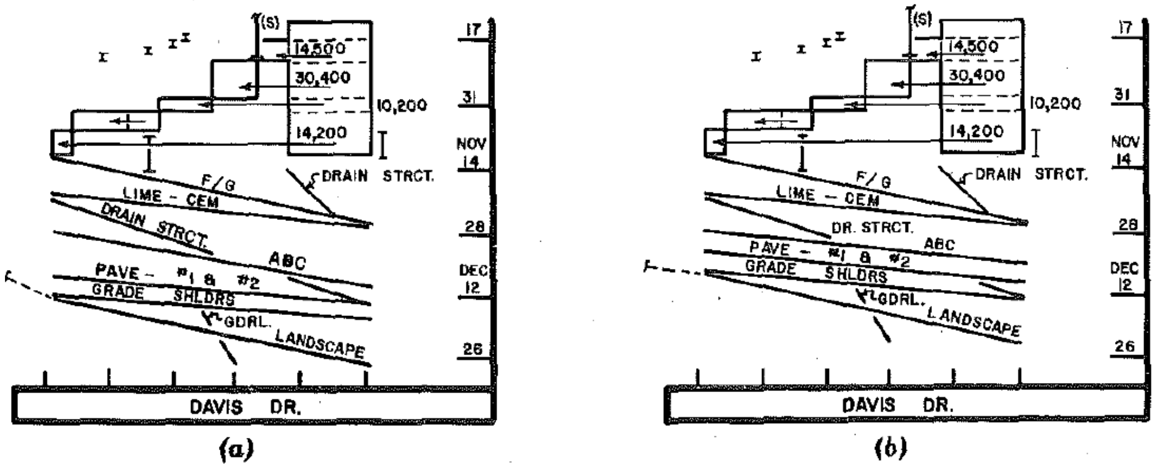


Figure 2-5 – Linear scheduling example from Chrzanowski and Johnston (1986)

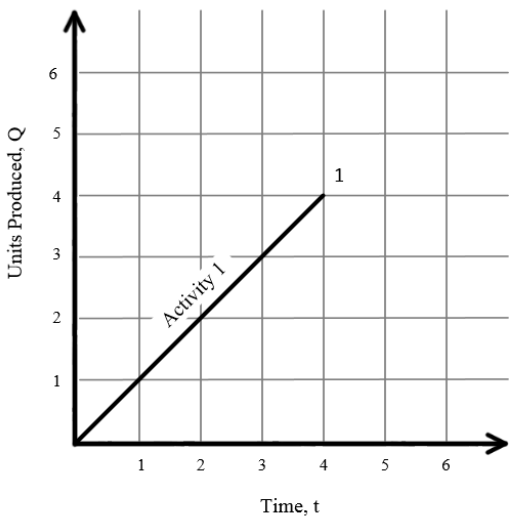


Figure 2-6 – Example of flowline diagram with one crew working on Activity 1

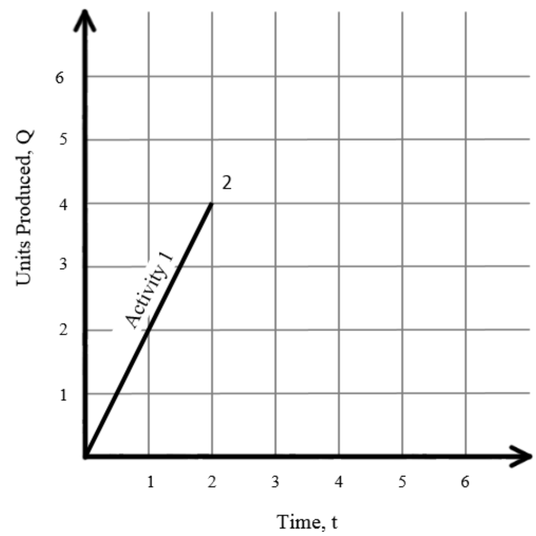


Figure 2-7 – Example of flowline diagram with two crews working on Activity 1

Arditi and Albulak's (1986) Line of balance technique provides a scheduling solution that articulates four criteria:

> "(1) A programmed rate of completed units is met; (2) a constant rate of repetitive work is maintained; (3) labor and plant move through the project in a continuous manner such that a balanced labor force is maintained and kept fully employed; and (4) the cost benefits of repetitive working are achieved."

Their work articulates these four goals, but the idea of "workable backlog" used in the Last Planner System and Takt time planning is not mentioned.

Suhail and Neale (1994) further developed the relationship between CPM and LOB. Harris and Ioannou (1998) expanded upon controlling the project duration, and noted that the critical path could be altered due to changes in resource continuity. Specifically, they demonstrated how accelerating some activities might paradoxically increase the overall schedule duration when activities are constrained to work continuously. This is an important consideration for Takt time planning and work structuring in general, for it may make more sense to slow some activities down if the goal is to improve the overall schedule.

Overall, Line of balance improved on the goal of maintaining resource continuity on repetitive projects. Repetition on these projects was in the actual work contents. Ideas surrounding a design of zones to produce flow, using workable backlog, or identifying workable backlog are not discussed.

2.3.2.3 Line of balance technique

Arditi and Albulak's (1986) case study provides a simple technique for creating a Line of balance schedule. This research adopts their equations for Line of balance scheduling to illustrate mathematically how simple (i.e., only repetitive) activities may be scheduled. For each activity, a Line of balance schedule requires finish-to-start relationships and activity durations based on crew sizes. From the durations, a scheduler can plot the number of units produced over time. The units can be specific distances (e.g., mile markers, linear feet, etc.), or more abstract (e.g., zones, areas, floors, etc.). Figure 2-8 reflects the progress of one crew producing (Q) units in time (t). This is a two-dimensional, deterministic representation of the crew moving through time and one dimension of space. Increasing the slope of the line, the production rate of the crew, doubles the amount of work completed by crew 1 in the same time (i.e., the time to complete each unit of work is reduced by one-half).

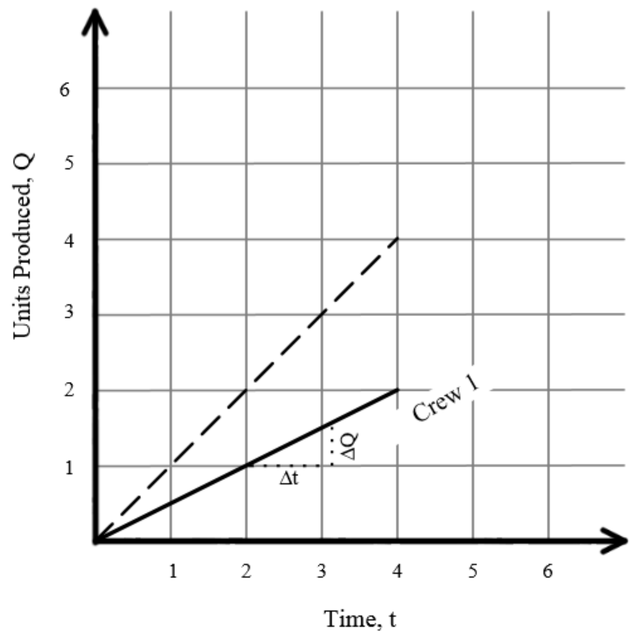


Figure 2-8 – Line of balance for one crew (increasing the slope to the dotted line requires a doubling of Crew 1's production)

The formula for the production rate, m (eq. 1), between the units j and i is:

$$m = \frac{Q_j - Q_i}{t_j - t_i}; i < j \qquad \text{(Equation 1)}$$

t_n = Time of start for unit n

Q_n = Number of units produced at n

m = Rate of production

The start times (eq. 2) for each unit i for an activity then are:

$$t_i^s = t_1 + \frac{(Q_i - 1)}{m} \qquad \text{(Equation 2)}$$

t^s_i = Time of start for unit i

Q_i = Number of units produced at i

m = Rate of production

t_1 = Time of start of first activity

The finish times (eq. 3) for each unit i for an activity are:

$$t_i^f = t_i^s + D \qquad \text{(Equation 3)}$$

t^f_i = Time of finish for unit i

D = Activity duration

This process can be done for all repeating activities. When plotted, one can visualize relationships that are difficult to identify with a CPM schedule (Suhail and Neale, 1994).

Figure 2-9 is a velocity diagram, plotting three crews from t=0 to identify their different production rates. Note that Crew 1 has a much slower production rate than Crew 2.

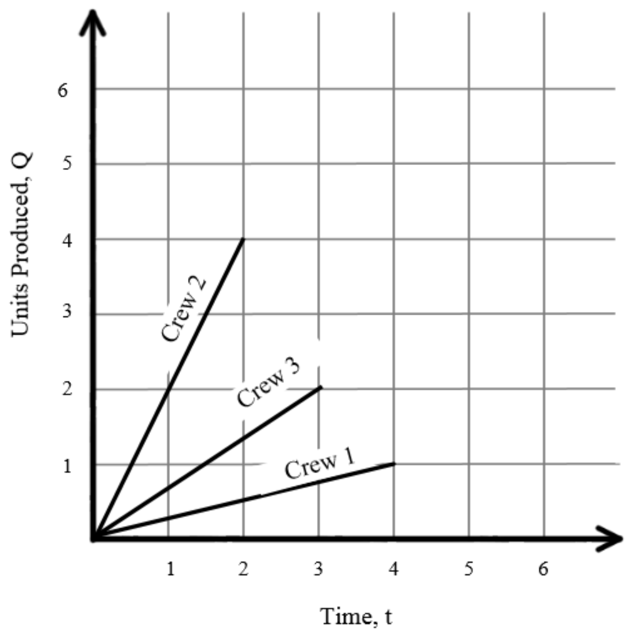


Figure 2-9 – Velocity diagram comparing production rates between different crews and their associated activities

Assuming that the crews work in a sequential order from Crew 1, to Crew 2, to Crew 3, then depending on when Crew 2 starts it is possible that the crew will continually catch up with Crew 1 and be forced to wait until the next units are ready (known as a production conflict). Figure 2-10 demonstrates this idle time occurring at one location; however, if the crews have different production rates and are scheduled close to each other, this relationship could continue throughout the whole schedule, resulting in a large amount of idle time for the second crew.

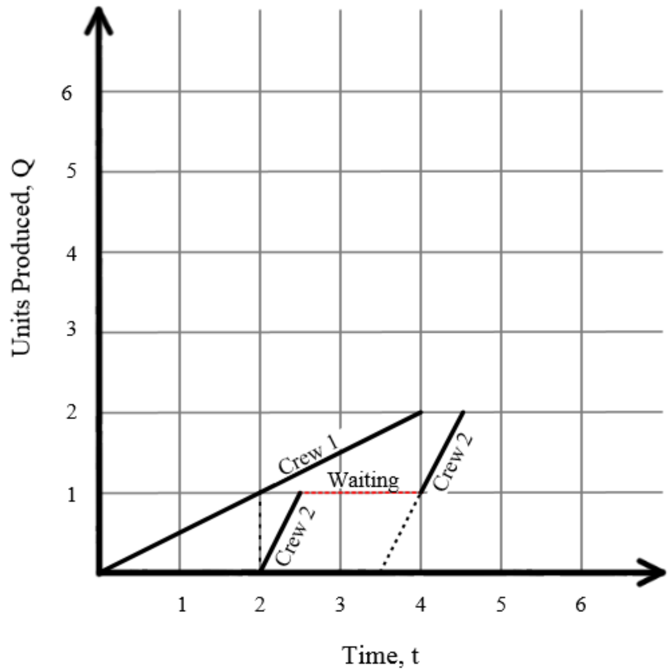


Figure 2-10 – Waiting as a result from production rate differences between Crew 1 and Crew 2

An initial goal of Line of balance scheduling is to identify these types of production relationships, and improve a construction schedule by speeding up or slowing down activities to create feasible workflows and efficiently use resources (Arditi and Albulak, 1986). After identifying areas of resource idle time and production conflicts between activities and their respective crews on an LOB diagram, a scheduler could revise the CPM schedule to create a more resource continuous schedule.

A resource continuous schedule is important to a general contractor, because it reduces the risk that a subcontractor will have to return on a specific date, since they are working continuously on the project. Thus, Line of balance helps to reduce schedule risk (i.e., the subcontractor not returning on time because they left due to a production conflict), helps to balance crews among trades, and can help to identify areas for improving the total cost (Sonni et al., 2004). In the case study from Sonni et al. (2004), a 30% reduction in required resources (in man-hours) was attributed to Line of balance scheduling.

Ideally, a scheduler revises the schedule to continuously use resources and create an even flow of work throughout a project in which all crews maintain the same production rate (or 'beat') (Figure 2-11).

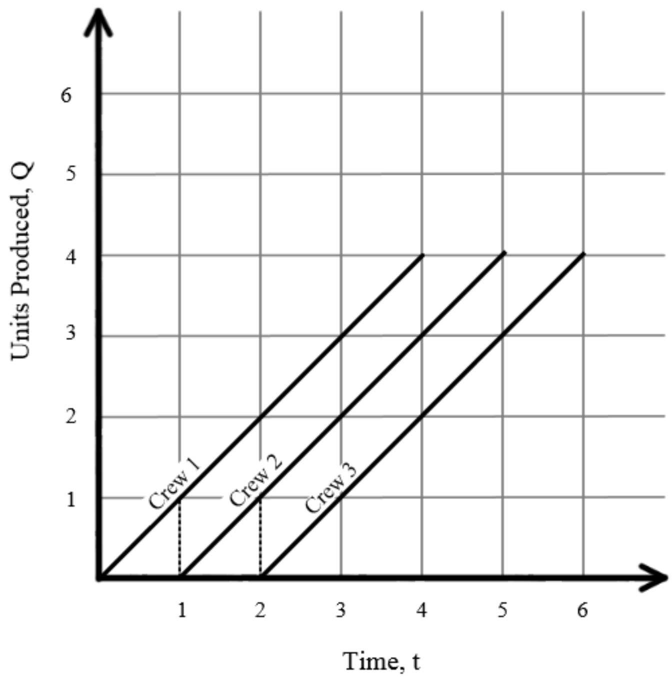


Figure 2-11 – Ideal Line of balance schedule with even flow and no waiting

2.3.2.4 **Challenges of Line of balance scheduling**

Several challenges remain for Line of balance schedules. CPM scheduling software was initially more prevalent due to its advantage of being easier to computerize (Chrzanowski and Johnston, 1986). A Line of balance schedule was initially perceived as a graphical tool that, while helpful, did not contain the same analytical capability as CPM schedule (i.e., it could not perform float calculations or reveal a critical path). Several researchers later showed that Line of balance schedules could perform the same CPM-related analysis and more (e.g., Harris and Ioannou, 1998, Harmelink and Rowings, 1998, Bonnal et al., 2005).

Line of balance methods contain several limitations. An inherent limitation is that a Line of balance schedule represents space in one dimension; thus, the actual workflow may be difficult to visualize if the "units" on the Y-axis are something other than a linear path (e.g., mile markers or floors) (Sonni et al., 2004). Figure 2-12 reflects a slightly more complex flow of work than a typical linear path. Numbers designate the completion sequence for separate units, and the hashed arrow shows how crews would move in succession accordingly. A Line of balance schedule will show activities moving in a line through the work sequence and abstract the circular (2D) work flow into 1D.

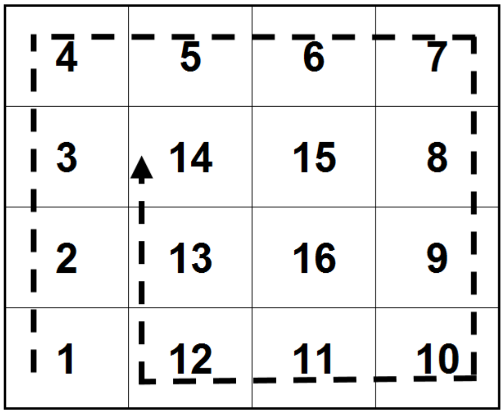


Figure 2-12 – Example of how 2D work flows will be abstracted out of a LOB diagram

Literature acknowledges three additional visual limitations. First, some activities may occur simultaneously on the same unit of work; thus, different line colors or styles must be used so activities are not 'lost' on the schedule (Arditi and Albulak, 1986). The scheduler must understand this relationship before scheduling the work to proactively make the visual changes. Second, due to looking different than Gantt charts, on-site managers and crew leaders do not always accept Line of balance schedules (Al Sarraj, 1990). Third, the schedule can quickly become a source of confusion for project teams when too many activities are plotted on the same schedule.

Additionally, Line of balance schedules are sensitive to production estimation errors (Arditi and Albulak, 1986). Figure 2-13 through Figure 2-16 reveal the sensitivity to production estimation errors in execution in the Line of balance schedule (Arditi et al., 2002). Assume finish-to-start relationships between Crew 1, Crew 2, and Crew 3 in sequential order. Figure 2-13 emphasizes how gaps in time and space between activities increase over time due to repetition. Figure 2-14 reveals the effects of overestimating production; the overestimation of Crew 1 in one area affects the following crew. Figure 2-15 shows Crew 2 catching up to Crew 1 due to a production underestimation by Crew 1. Due to their initial network relationship, a delay in Crew 1 will affect Crew 2. Finally, Figure 2-16 identifies that increases or underestimations in production rates of a crew (Crew 2) delays future start times for other crews (Crew 3) (Arditi et al., 2002). One method for mitigating schedule uncertainty and reducing the impacts of crews on each other is to increase time buffers between (in this case, place time buffers between crews 1 and 2, and crews 2 and 3) (Arditi and Albulak, 1986; Howell et al., 1993). While Line of balance schedules are sensitive to this issue, it also makes the problem of incorrect production estimation visual; thus, from a lean perspective, it can be a good tool for project teams because it helps to identify unwanted variation.

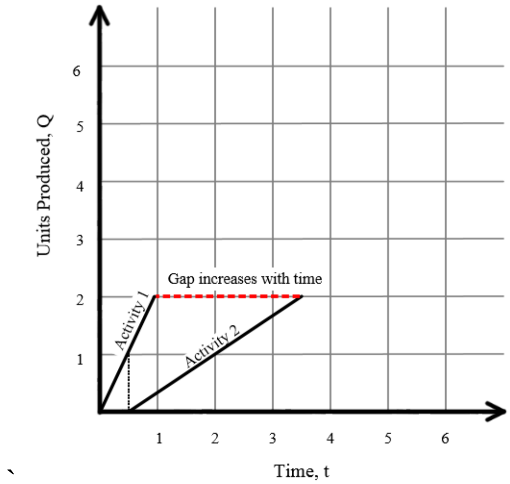


Figure 2-13 – Gaps between crews increase with time

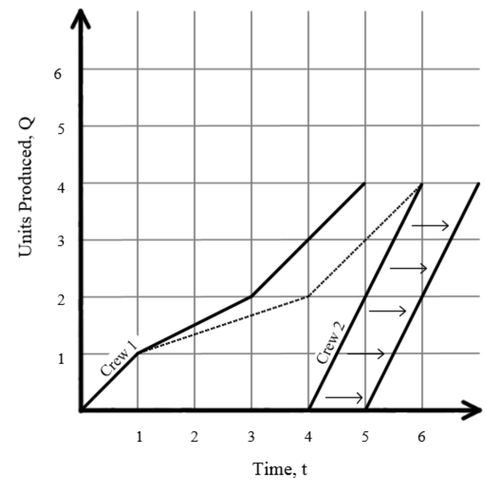


Figure 2-14 – Production overestimate affects schedules

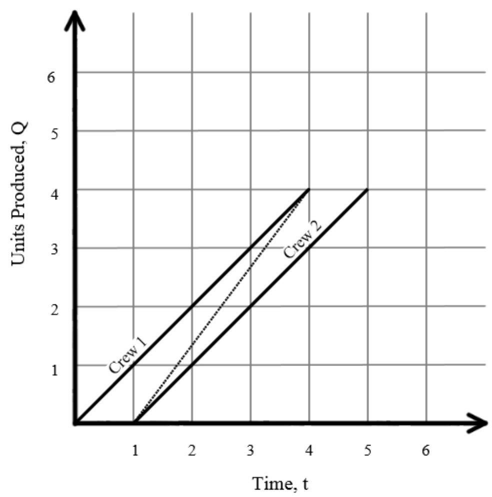


Figure 2-15 – Crew 1 and 2 finish at same time because of underestimation

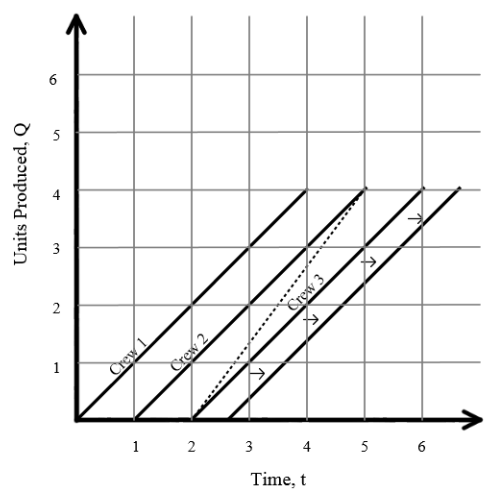


Figure 2-16 – Increasing Crew 2's production rate affects Crew 3's starts

Project teams using Line of balance schedules must also consider how to discern between repetitive and non-repetitive work, and schedule the work accordingly. Non-repetitive activities can be difficult to schedule, as the units may be different than the units defined by the repetitive activities in the LOB schedule (Arditi et al., 2002).

Arditi et al. (2002) demonstrated how the critical path from a Line of balance schedule might differ from a network diagram for a single unit of work. This may be the case because producing a single unit of work is different from the whole project; thus, scheduling repetitive work will reveal new bottleneck activities that would be unforeseen when looking at a network diagram for a single unit.

Line of balance schedulers typically use a constant rate of production over time for similar production areas. However, as crews repeat activities, the they will naturally improve upon their productivity due to learning (Arditi et al., 2001). While there is limited research on the topic, Line of balance schedulers typically do not account for learning curves. In addition, assuming the same production rate through every unit of work for an activity may reveal an incorrect critical path through the project. This is not necessarily a limitation of LOB scheduling, but the critical path in a LOB schedule is highly dependent upon the input production rates (just as a CPM schedule is dependent upon activity durations).

From the perspective of an individual subcontractor, Line of balance scheduling may compromise their crew size optimality (Arditi, 2002). A Line of balance schedule may dictate that they maintain a higher production rate with more crews, resulting in "over manning" and lower productivity (per worker). Conversely, a Line of balance schedule may reveal that the workflow of an activity must be slowed down. Regardless, adjusting from the optimal crew size may be justified in order to improve the overall workflow on site. The commercial terms of the project help to determine if a subcontractor will be in favor of adjusting their crew sizes to improve the project overall. Thus, if a project incentivizes subcontractors to improve the project overall, the subcontractors may staff the project accordingly. Determining the right crew sizes is part of the work structuring problem on which Takt time planning aims to provide guidance, and will be discussed in detail later.

Line of balance schedule optimization is not a focus of this research, but is a related and well-researched topic. Schedules may be optimized using various types of algorithms for different parameters with different weights across cost, time, resource continuity, and resource utilization (e.g., El-Rayes, 2001; Hegazy and Wassef, 2001; Bonnal et al., 2005; Vanhoucke, 2006; Luong and Ohsato, 2009; Damci et al., 2013; Bakry et al., 2014).

2.3.2.5 **Conclusion**

At its outset, Line of balance scheduling addressed shortcomings in CPM scheduling by making resource continuity and production rates visual. This is an assumption and objective of Line of balance scheduling: keep resource use continuous and schedule resources to full utilization to improve the schedule. However, Line of balance scheduling adoption by industry was limited, in that its schedules were harder to computerize; thus, CPM and Gantt charts maintained their popularity, in particular with field personnel, project managers, and owners who have asked to see "bar charts" (CPM schedules) over Line of balance schedules. Visually, Line of balance schedules can become cluttered with too many activities and require careful management in order to maintain their effectiveness. Line of balance schedules are deterministic models of the schedule, and represent space in one dimension; thus, positive or negative variations in production rates and actual space are difficult to represent.

2.3.3 LOCATION-BASED MANAGEMENT SYSTEM

Seppänen (2009) used case study research to study Location-based Management System (LBMS) in construction. LBMS is a method for producing flow in construction by using buffers in time to protect individual flows for subcontractors from interference by other activities (Kenley and Seppänen, 2010). The system uses space as a resource, and describes how to plan and control a project using Line of balance scheduling. The general contractor managing the schedule gathers production rates of activities through zones as they are completed. LBMS uses the actual production data to predict schedule conflicts between activities in space, and constantly updates the schedule to identify and resolve these production problems before they occur. For these reasons, it is a system worth exploring in order to create a new work structuring method.

Seppänen identified that: (1) interior construction offers a major improvement opportunity for general contractors; and (2) "cascading delay chains" create a large portion of plan failures. Cascading delay chains are linked activities where the first activity in a "chain" (a series of activities) does not complete as planned, due to an incorrect production estimate and the delay affects succeeding activities. (3) While location-based methods of planning begin as "push" systems, LBMS considers the capacity of downstream customers. (4) Seppänen also recognized that work was executed out of sequence, production locations changed frequently, and slowdowns occurred due to production rate inaccuracies, despite using a location-based schedule. (5) Seppänen noted that the construction team followed the plan while the researcher is on site, but activities fell back to traditional methods when the researcher left.

One gap in the research was the lack of a discussion about a method or any criteria for selecting zone sizes. Similar to Line of balance research, the zones are a "black box" (i.e., they simply appear). The zone sizes are typically large (an entire floor, one mile of road, one-half of a floor, etc.), but there is little explanation or method on how the zones are created. Seppänen (2009) provides a guideline: "the lowest level locations should be small, such that only one trade can effectively work in the area." He did not mention any iterative process for designing the zones based on the subcontractor input, though Seppänen states that production problems arise due to the infeasibility of the work zones for certain subcontractors.

Later LBMS research has also explored how LBMS can be combined with the Last Planner System to plan and control production on projects (Seppänen et al., 2010; Seppänen et al., 2015)

2.3.4 SPACE PLANNING

Other researchers have explored different methods for incorporating space into construction planning. This study uses the term "space planning" to categorize these efforts, including those of Tommelein (1989), Tommelein and Zouein (1993), Thabet and Beliveau (1994), Riley and Sanvido (1997), Hessom and Mahdjoubi (2004), and Akinci et al. (2002).

Tommelein (1989) and Tommelein and Zouein (1993) provided a tool for managing and modelling changes to temporary facilities, material flow, and equipment use on projects. Their term for this was dynamic layout planning, for which they developed prototype software called MovePlan. MovePlan required dimension data for all modelled objects, in addition to schedule information (activity, activity duration, network logic, and associated resources). The software created a 2D representation of how the schedule changed resources on site, and created histograms for resource use. The purpose of this dynamic layout planning was to aid the development of a space schedule, and start with the most congested layouts with unmovable items.

Thabet and Beliveau (1994) modelled workspace use in multi-story building construction. Their method identified three classes of space demand for each activity. (1) Class A activities require the entire space scheduled to the activity only. (2) Class B activities require a fixed amount of space, but not the entire space such that other activities may be scheduled concurrently, as space is available. (3) Class C activities require staging of material before the activity begins. The research also provided a method to model space in order to acknowledge the relationship between productivity and scheduling work in congested environments (Figure 2-17) (Thabet and Beliveau 1994). The figure helps visualize the relationship and is not empirical.

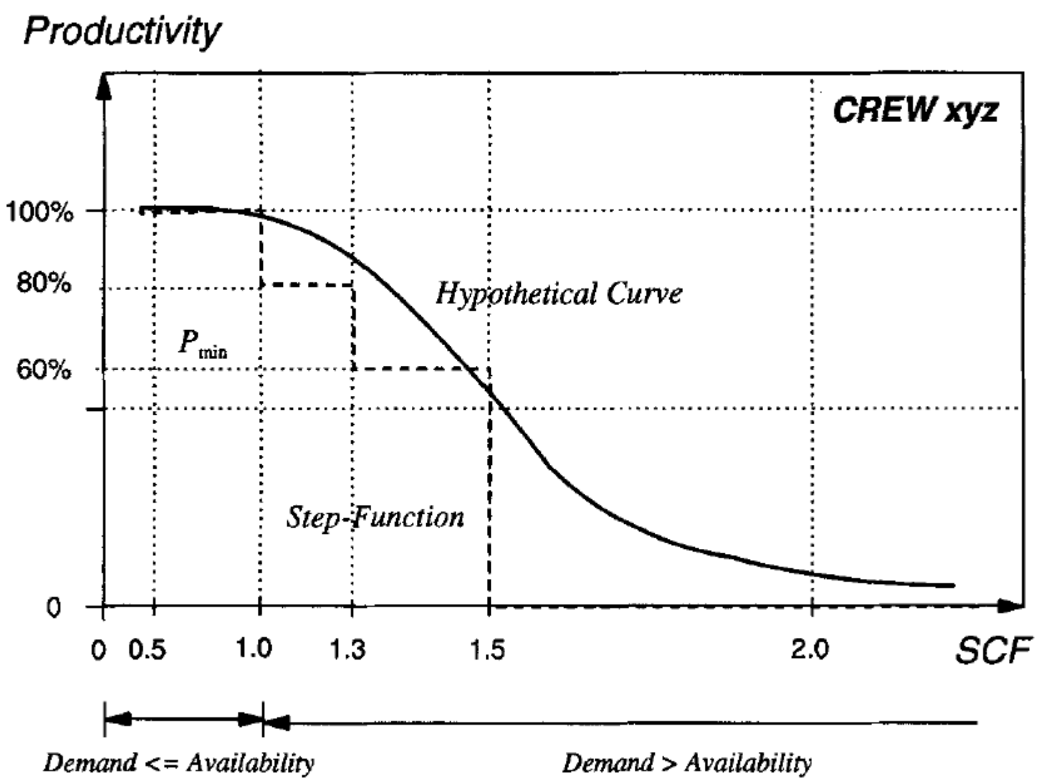


Figure 2-17 – Space Capacity Factor versus Productivity (Thabet and Beliveau, 1994)

Riley and Sanvido (1997) presented a 16-step method for space planning in multi-story construction highlighting that it is critical for a team to identify storage and work areas in order to avoid work conflicts. They reduce their method to four general steps: (1) identify space constraints; (2) identify space layout; (3) sequence the work; and (4) resolve conflicts. They tested the method on four concrete structures, ranging from 3-9 floors. Findings from their case studies using the method were: (1) crews worked more productively if given more space; (2) space planning helps to identify which materials can be delivered to the site; (3) detailed planning was viewed as wasteful by construction practitioners, despite the space plan's ability to catch space conflicts; and (4) more detailed tools need to be developed linking design to construction schedules.

Due to improvements in computing and the capabilities of building information modelling software, including space as a resource in the schedule has become more prevalent in the past two decades. Akinci et al. (2002) aimed to automate the generation of a 4D CAD simulation It performed time-space conflict analysis using unique industry foundation classes for elements that considered the space required method to install different building components. Hessom and Mahdjoubi (2004) identified the trends in 4D CAD beginning in the 1990s. One trend identified that still exists today, is that 4D CAD's primary use is a communication tool to explain design and construction plans. Since 2011, Autodesk has provided this 4D capability in Navisworks (Autodesk, 2011).

Research in space planning is important to Takt time planning for several reasons. The research expanded on the idea that space is important to include in a schedule when considering material flow, work space, equipment use, and temporary facility location or material storage. When planning, it is also important for a team to consider that different types of activities use the space. Last, space planning research shows how BIM can be used by a team to plan the work and better understand how to execute a project.

2.3.5 Week-beat Scheduling

Court (2009) used a Takt time of one week to schedule mechanical and electrical component installation in one-week intervals in order to keep trades in different work zones and prevent crew interference. The research defined this type of scheduling as "Week-beat scheduling." All work was pull planned to identify specify trade sequence, and the research described a method for creating zones. The method involved splitting work into approximately 1,000 m^2 zones sized to require one week of installation time by a crew for most of the activities, and controlled with the Last Planner System.

"Week-beat scheduling" requires the following:

- "Each team has to work at the rate at which the previous team makes the working area available to them in order to provide a continuous flow of work (the rate of sales – Takt time);
- The size of each team may be increased or decreased, but the actual pace of physical effort is never changed (subject to resource management);
- Each team has to carry out their designated amount of work in the planned time in order to make the working area available for the subsequent trade team;
- Each team must be able to complete their work in the zone and move to the next zone without waiting for it to become available or starting early;
- The systems being installed must be designed to facilitate this process;
- The rate at which each item of work is carried out is to pull materials onto the site to the work area on a Just-In-Time basis, specifically for the task, and without being stored on the site, in kit form, on mobile carriers or roll cages;
- Access equipment and tools are to be designed specifically for the area in which the work is to be carried out, and the rate at which the work is to progress;

- The rate at which each item of work is carried out is to pull current drawings and information onto the site.

Like Line of balance scheduling efforts, Week-beat scheduling appears to emphasize resource continuity and avoids workers waiting for work. A gap in this research is that there was no rationale provided for Week-beat scheduling (Court 2009), likely because it was not the focus of the research. Court did not specify why a "week's worth of work," 1,000 m^2 zones were chosen, how the crew sizes and work methods affected the design of zones, or what sort of production-related data was required to create the zones. The research cites Horman et al. (2002) as inspiration for the Week-beat schedule. Horman et al. also used a Week-beat schedule to work on the renovation of wedges 2-5 at the Pentagon. This research called the method Short Interval Production Scheduling (SIPS), and cites Burkhart (1989) on the topic.

Court (2009), via Week-beat scheduling, proposed but did not elaborate on: (1) using buffers in capacity to deal with production variation; (2) designing zones as a function of installation hours required in the area; and (3) aligning groups of activities to the same pace. Regardless of the method gap, reliably handing off work was beneficial for the project (Court, 2009). The project realized a 37% savings in on site hours due to the production planning and control system used on site, despite planning to 80% production capacity. In all, there was a 7% cost savings in the budgeted labor.

2.4 LAST PLANNER SYSTEM

Production planning and control are important in construction in order to deliver projects successfully (i.e., safely, on time, under budget, and with quality). The Last Planner System is a production planning and control system used in construction, and helps to increase plan reliability by dividing planning into three distinct processes that focus on different levels of detail (Ballard, 2000). The rationale for splitting up project planning is that the further out and more detail one plans to, the more incorrect will be the plan.

The first step in the Last Planner System is to identify what should be done via the Master Schedule and Reverse Phase Schedule meetings (Ballard and Howell, 2003). The Master Schedule defines the milestones dates for the project. Reverse Phase Schedule meetings provide the team the opportunity to pull plan from milestones in order to validate the schedule. Working backwards and pulling the work helps the team identify the work from one trade that releases work to other trades. The Reverse Phase Schedule meetings also identify the allocation of float in the schedule.

The second step is for the team to turn work that should be done into work that can be done through a Make Ready process. Ballard and Howell (2003) identify three categories of constraints for activities: directives, prerequisite work, and resources. Directives consist of the information required to produce the desired output (e.g., design documents, specifications, task assignments, etc.). Prerequisite work consists of the work that must be completed before the activity starts. The resource constraints are labor, equipment, and the space required to perform the activity. Koskela (1999) also provides seven similar pre-conditions to any construction activity: (1) design, (2) components, (3) materials, (4) workers, (5) space, (6) connecting work, and (7) external conditions. Work is made ready by creating a Look-ahead schedule of the upcoming six (or more if necessary) weeks of schedule activities and performing constraints analysis. The number of weeks to look at depends on how long it takes to make the work ready. If an activity has a 12-week lead time, then it needs to be ordered at least 12 weeks out, or it will impact the schedule. If any upcoming activity has a constraint, the team should track and solve it before it impacts the schedule. If the constraint cannot be removed in time and impacts the schedule, it should not move forward in the plan, and the team should plan the work.

The final objective is to commit to work that will be done via the commitment meeting. A commitment meeting typically occurs on a weekly basis, and is also known as the Weekly Work Planning meeting. The commitment meeting first identifies work that should and can be done. The Last Planner, the individual who will be in the field directly managing or performing the work, accepts, and then commits to completing the assignment. This work becomes the work that will be done. Assignments should meet four criteria: (1) definition, (2) size, (3) sequence, and (4) soundness and learning. In summation, the Last Planner System identifies the work that should and can be done, then tracks the commitments for what will be done and what was actually done so the team can understand (and mitigate) the root causes to variances from the plan (Figure 2-18).

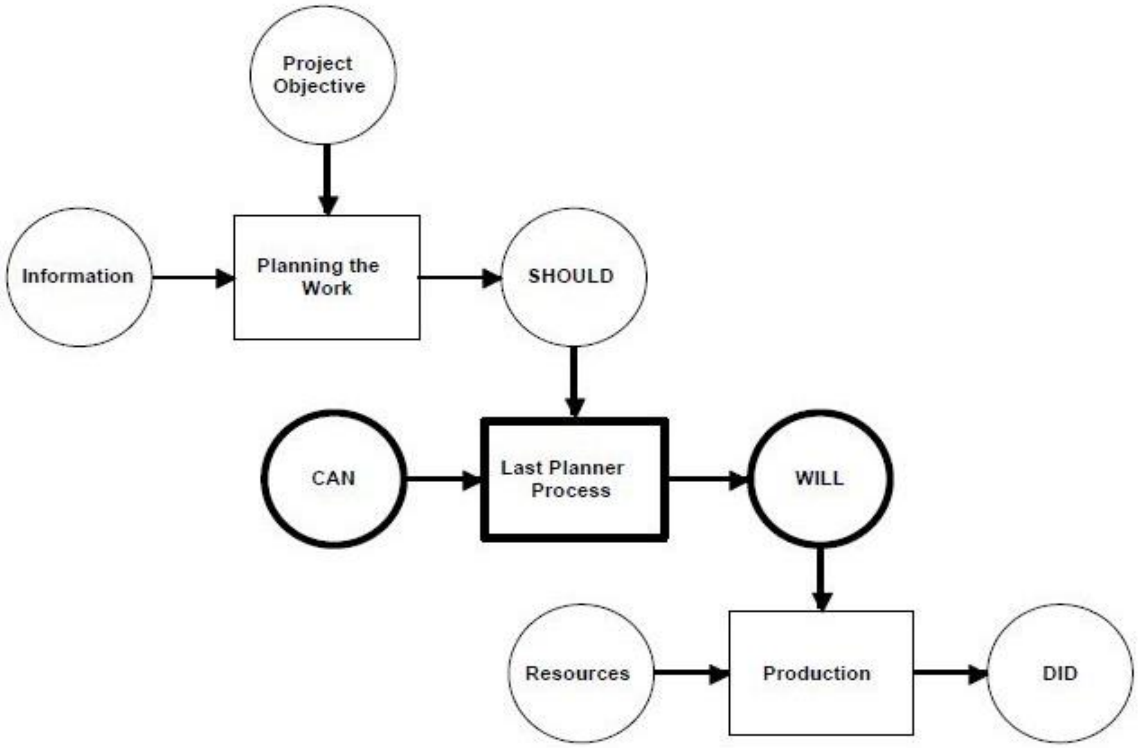


Figure 2-18 – Overview of the Last Planner System (Ballard and Howell, 2003)

2.5 TAKT TIME

2.5.1 DEFINITION OF TAKT TIME

Takt time is a unit of time. 'Takt' is the German word for 'beat' and refers to the regularity in which something is completed. Takt time, however, is much more than simply a beat, for it is used in production systems to align production rates with demand rates (e.g., the pull of the customer). For this research, Takt time is a design parameter used in a production setting (manufacturing, construction, or other) (Hopp and Spearman, 2008), defined as: *the unit of time within which a product must be produced (supply rate) in order to match the rate at which that product is needed (demand rate).*

2.5.2 TAKT TIME IN MANUFACTURING

Takt time is known for its wide use in the Toyota Production System. However, Takt time was initially used in the 1930's in the German aviation industry to pace assembly of airplane fuselages (Womack, 2004). In the 1950's the idea of Takt was used in Toyota shortly after another local company, Mitsubishi, started using the concept. Developing a Takt that matches the capability of all workstations in a line (or system), and vice-versa, adjusting the capabilities of workstations to match Takt and is critical to promoting flow in production systems. Two problems occur when Takt time and workstation capabilities are greatly unmatched. Either product will accumulate in-between workstations when the next workstation is not yet ready to perform its operation on the product, or a workstation will starve (i.e., wait for work) when it performs its operations much faster than its predecessor. Variation in production and demand rates makes this balancing act more challenging.

Designing with Takt time as a parameter fosters a pull system of production. Pull systems are demand-rate driven; designing for demand rates allows production systems to maintain a steady flow because output rates match demand rates. In contrast, push systems are plan- or forecast-driven; output rates may or may not match demand. Hopp and Spearman (2004) cite the following benefits to using a pull system: smoother flow, lower work in process, improved quality, and reduced costs. Enabling a production system to continuously flow helps surface production problems, so they can be addressed (Liker 2006). The production problems surface because the Takt time sets a minimum output rate. When all operations are aligned to the same rate, deviations in production rates from the Takt time can be observed, understood, and systematically rooted out through counter measures and updating standard procedures (Adler et al., 2007). In the Toyota Production System, this problem-solving process is known as the hansei process (meaning "reflection review").

2.5.3 TAKT TIME PLANNING IN CONSTRUCTION

Takt time planning is a work structuring method that aligns the production rates of trades by pacing work through a set of zones in a set sequence to create continuous workflow, reliable handoffs, and an opportunity to continuously improve the production system. Creating the set of zones is a design process. The goal is to have all of the activities in the sequence contain the same amount of work in each zone; this is how construction can adapt Takt time to a non-repetitive setting. The motivation to use Takt time planning (TTP) in construction is to take advantage of the more predictable environment created by the Last Planner System. In the context of the Toyota Production System's continuous improvement spiral (Figure 2-19), the Last Planner System provides the first step of "stabilizing," and Takt time planning provides the means of "creating flow" (Liker, 2006). Thus, Takt time also provides a mechanism for a team to systematically improve over time by improving upon a Takt time in small increments.

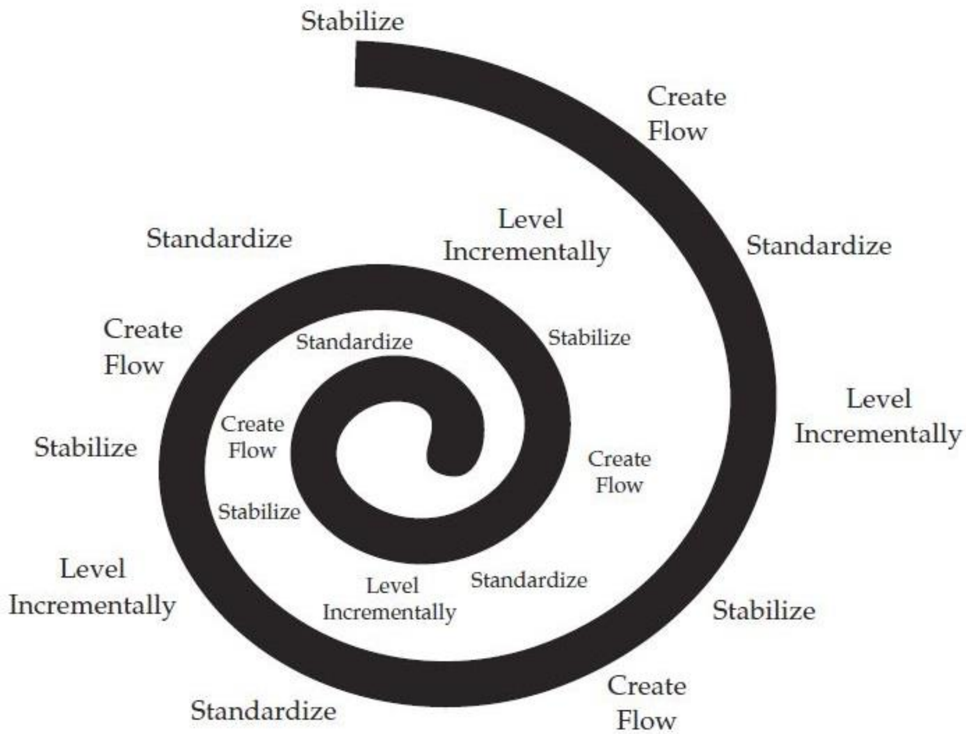


Figure 2-19 – Task improvement in the continuous improvement spiral (Liker and Meier, 2006)

Takt time planning in construction is different from implementing it in the manufacturing context. In construction, workers move around the work, as opposed to the work moving to the worker (i.e., via an assembly line) (Ballard and Howell, 1998a). In addition, this question arises: What is the demand rate on a construction project when the team is not producing widgets at a specific rate based on customer demand? There is a known completion date for the project based on when the owner requires it, but that is negotiated and can change. As such, using Takt time planning in construction requires that the project team create their own demand rate aligned with the completion date that can be translated into different types of units. General units could be those into which a team breaks the project down; this research calls them zones through which different construction activities will move. More specific units could relate to individual work components for each trade (i.e., linear feet of walls, duct, piping, etc.).

A difference between Takt time planning and other location-based planning methods is the balance between "work waiting on workers" and "workers waiting on work." Work waiting on workers on a construction site is idle space that is work in process (Faloughi et al., 2015). Workers waiting on work occurs when a crew does not have available work, and must wait for work, move off the project, or engage in another activity. Recall how Line of balance scheduling aimed to maintain continuous resource use, or minimize workers waiting on work. While this is an important consideration when structuring work, it may be necessary to buffer with working capacity (i.e., allow some waiting on work) to achieve better workflow for the entire production system. How much capacity to use as a buffer is a production system design decision.

In construction, pacing sets of work at the same rate is not necessarily new. In addition to the cited work related to location-based planning efforts, practitioners in the U.S. housing industry have been using demand management and 'even-flow production' to balance resources and reduce cycle times for repetitive work (Ballard, 2001, Wardell, 2003, Bashford et al., 2004, Yu et al., 2009). Bulhoes et al. (2006) demonstrated that controlling the production of a concrete structure using small, repetitive cycles resulted in improvements in productivity, as well as reductions in cycle times and waste. Takt time has been used successfully in home building (Wardell, 2003), modular home manufacturing (Valarde et al., 2009), and highway construction (Fiallo and Howell, 2012). Dlouhy et al. (2016) refer to early research from this dissertation and describe a method for Takt time planning for repetitive structural and foundation work in construction. However, little has been documented to date regarding what method can be followed in non-repetitive interior construction to design a production system with Takt time.

Takt time is a demand rate (e.g., time/unit), and the denominator depends on perspective. The general denominator in this case is a zone; a 'four-day Takt time' would employ a system where activities complete in less than four days. The zones are comprised of different components depending on the type of work, so the demand rate may be translated or reduced into smaller units. For example, a drywall trade contractor may have the standard four-day Takt time through a zone that requires him to frame 500 linear feet of wall. While the Takt time is four days, the denominator could be general - per zone, or specific to the zone and trade: per 500 linear feet of wall. The Takt time may also translate to a daily Takt - five days per 500 linear-feet becomes one day per 125 linear-feet. Using the zones builds a common language for the team to use when discussing their work. This is important for describing demand rates in a common way, and for discussing how crews move through the space. Finally, the inverse of the Takt time would be the minimum production rate required in units per time.

Recently, Takt time planning research was published in Germany. Binninger et al. (2017) discusses the use of Takt time for repetitive construction work, and cites manufacturing influences (in German) from Kaiser (2013) and Friedrich et al. (2013). Theis (2017) uses a similar Takt time planning process that begins with identifying different work areas, and then produces a paced repetitive sequence for each area. In all, that body of Takt time research applies Takt time planning in repetitive settings.

2.5.4 Takt Time as a Work Structuring Method

Work structuring is a part of production system design that answers the following questions (Ballard, 1999; Tsao et al., 2000):

- "In what chunks will work be assigned to specialists?"
- "How will work chunks be sequenced?"
- "How will work be released from one unit [one trade crew activity performing an activity] to the next?"
- "Where will decoupling buffers be needed, and how should they be sized?"

- "When will the different chunks of work be done?"
- "Will consecutive production units execute work in a continuous flow process, or will their work be de-coupled?"

Tsao's (2005) dissertation on work structuring in construction observed work structuring practices in three case studies: (1) hollow metal door frames; (2) at a lighting supplier; and (3) stone-on-truss curtain walls.

Tsao made several findings and contributions to project-based production theory. The first finding was that whether design professionals realize it or not, they are defining means and methods when they create design specifications. The second finding was that moving work upstream improves project delivery. This is similar to Shingo's (1988) notion of process-oriented processing improvement, where the best improvement eliminates the need for additional downstream operations. The third finding was that contracts affect systems thinking and work structuring efforts, so it is important to form contracts with suppliers early on to benefit from their full engagement. The fourth finding was that (traditional) habits prevent innovation in work structuring by preventing team members from considering alternative work methods.

While Tsao (2005) acknowledges different work structuring efforts from the 1960s, on, her research was the first attempt to study the subject in depth in a construction setting. One outcome was a language for work structuring found in literature she researched:

- Work chunk – A unit of work one production unit hands off to the next production unit
- Production unit – A group of direct production workers who do or share responsibility for similar work, drawing on the same skills and techniques
- Handoff – The combined completion of a work chunk by a production unit that: (1) allows a subsequent production unit to further transform the work chunk or execute a different work chunk as planned; (2) declaration of completion of the work chunk by the production unit and release to the subsequent production unit; and (3) acceptance of the released work by the subsequent production unit.

This dissertation aims to fill some gaps identified in Tsao's research on work structuring. The research assumed that project participants were able to coordinate and balance their production system, though little to no method exists in interior construction to do so. In addition, the case studies primarily focused on work structuring at a task level.

In relation to the triads of the Lean Project Delivery System (Figure 2-20), Takt time planning should begin in the early project definition phase of a project because it is a work structuring method (Ballard and Howell, 2003). During project definition, the project team should consider how fast work can be completed, versus how fast the work should be completed. Matching customer demand with the means and methods available is critical, but equally important is validating that the customer demand is within the means of the team.

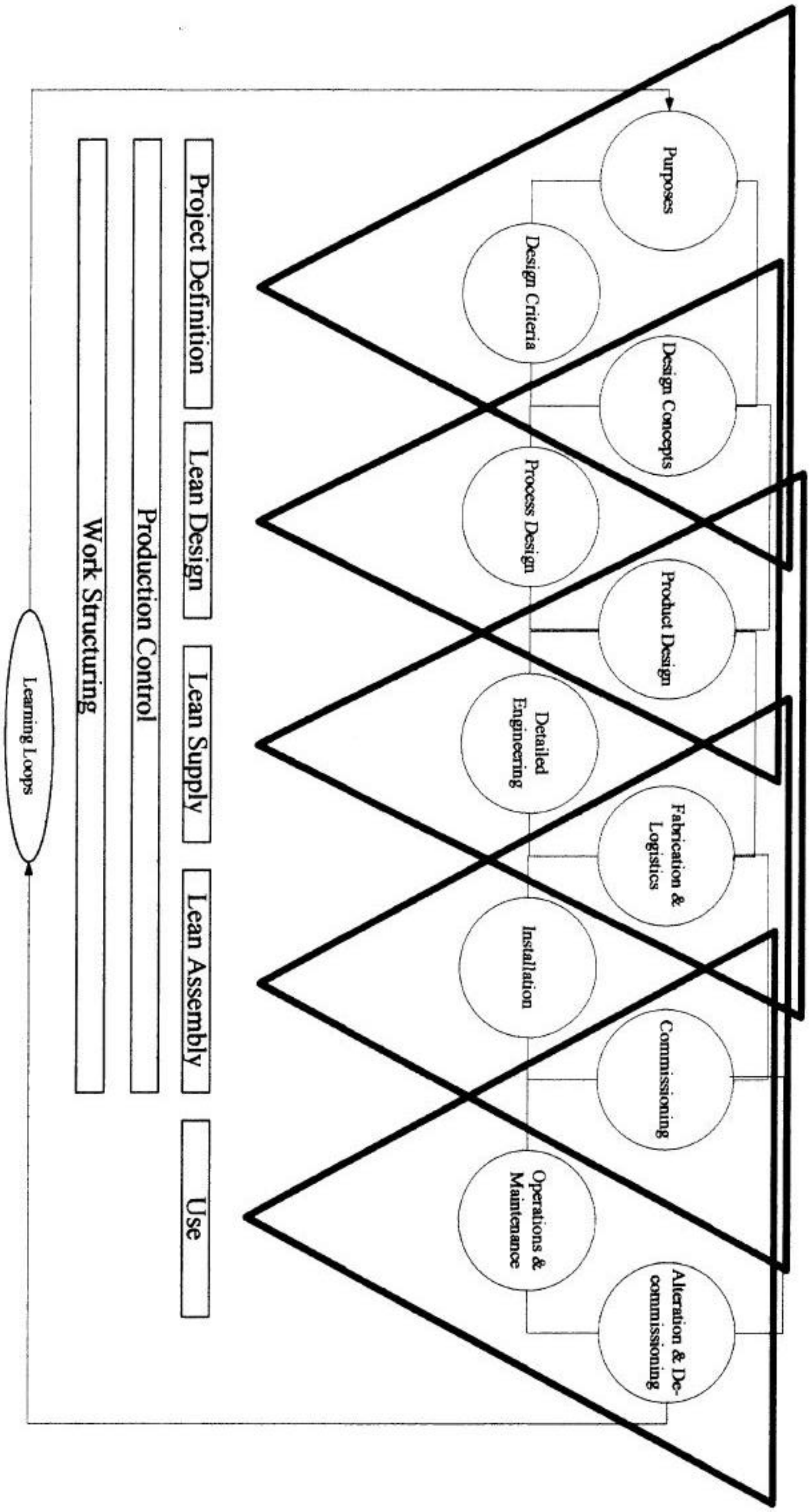


Figure 2-20 – Triads of the Lean Project Delivery System (Ballard and Howell, 2003)

There are two alternatives for matching. One is that the owner's demand can be matched, enabling the team to work to produce a schedule where trade crews progress at a rate that delivers the project to the customer when they need it. The second alternative is that the demand exceeds the rate at which the team can produce. In this circumstance, the succeeding steps may be to identify the maximum production capacity of the slowest trade, work to improve upon that capacity, align the other trades to match that capacity, and use that as the feasible demand rate for the project that is communicated to the owner.

Takt time sets an upper-bound on the time any single trade is afforded to take in any one zone. When the Takt time is set higher than the required duration for a trade, the trade will have idle time, or a capacity buffer. Some capacity buffer may be desirable to accommodate variation in the production system. Trades with too much idle time may opt to decrease their crew size, perform workable backlog elsewhere, etc. However, if the Takt time is lowered, then more trades will be increasingly likely to exceed it.

Figure 2-21 demonstrates how Takt time planning impacts work structuring questions and work methods. On the X-axis are different work methods and crew configurations in clusters, working through different zones. The selection of a Takt time may render certain work methods and crew configurations infeasible. In this circumstance, if a five-day Takt time is required, then the two options to meet the Takt time are: a crew size of six, or a crew size of three using prefabricated components.

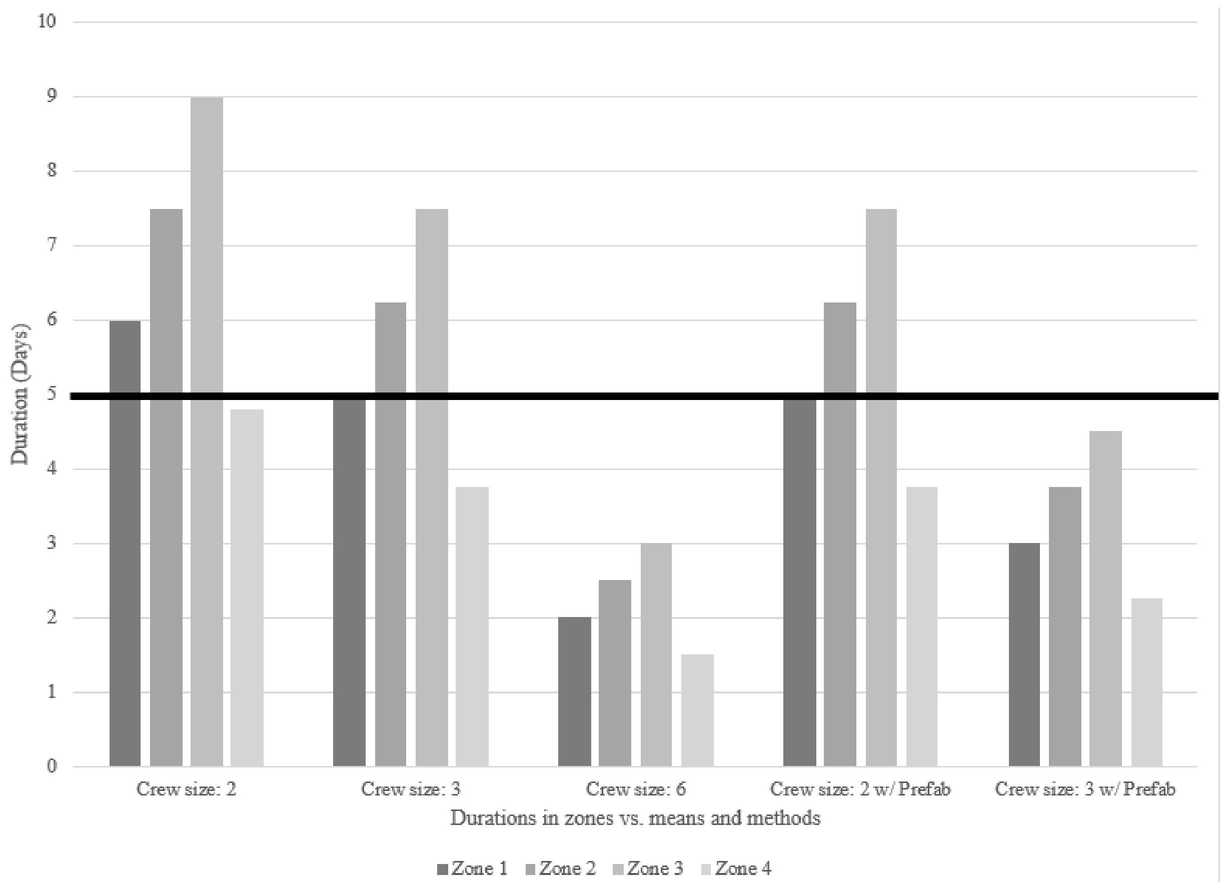


Figure 2-21 – Selection of Takt time versus trade-specific activity durations in each Zone

In summary, introducing Takt time into construction is an attempt to move from uneven activity durations for each trade in a sequence, to a consistent activity duration for every trade, while maintaining a production rate that meets the requirements of customer (via the Master Schedule). To accomplish this, for each phase of construction, the project is broken down in physical areas (zones) where trades may spend up to a certain amount of time (the Takt time) to complete their work. Defining these zones, breaking the work into phases, and setting the rate trades can move through them is a design problem.

2.5.5 COMPLEMENTS OF LAST PLANNER SYSTEM AND TAKT TIME PLANNING

The following section contains a list of the ways Takt time planning and the Last Planner System complement each other. Overall, Takt time planning complements the Last Planner System by introducing continuous flow and more standardized work for the Last Planner System to control to, and the Last Planner System provides the mechanism for control, mechanism to make work ready, and the ability to facilitate planning where continuous flow is not possible (and where it is possible). These findings come from Case Study 1 and meetings with industry practitioners using Takt time planning, and were discussed in (Frandson et al., 2014). The Last Planner System is not necessary for implementing Takt time planning, but the alternative should offer the Last Planner System complements provided in the succeeding section.

2.5.5.1 Last Planner System complements

Facilitates irregular variances: The Last Planner System complements Takt time planning by facilitating irregular variances of work where continuous flow is infeasible. The Last Planner System accounts for "go-back" work, specialized access areas, and work in process.

Facilitates low-level variation: The Make Ready process and Commitment Planning provide the mechanism to manage variation at the operation level. The PPC metric accounts for this variation. While the Takt time planner would consider the variation "noise" if it does not affect the handoff of work, the Last Planner System is the means to obtain the data. The Last Planner System also provides a means for managing with the new activity sequences through missed zones (zones where a Takt time was missed for an activity) that could not follow the initially planned activity sequence.

Provides control system: The Last Planner System provides the structural system to facilitate Takt time planning. Takt time planning is the process of sequencing and leveling production through similar areas of work density, but it still requires a method of controlling the production schedule.

Engages workers: The Last Planner System is a process that engages the foreman, the Last Planner, in the actual planning of work. The Last Planner is encouraged to offer up his practical wisdom and reject assignments that do not meet the four quality criteria (definition, size, sound, and sequence).

2.5.5.2 Takt time planning complements

Pace: Takt time provides the project with a feasible pace and work flow that – at a minimum – meets the customer's demand rate. This provides two benefits. First, pacing provides activities of the correct size and sequence to the Last Planner (the foreman planning the work) and a clear outlook on upcoming work. Second, a planned workflow reduces stress on the foreman by giving him a clear, concise target; as long as the foreman is on track for completing the small batch of work assigned in the Takt time sequence, he is on track for the entire project.

Increased focus and simplification of the Lookahead process: Takt time planning provides staff with focus and priority for their work on site. The Lookahead process is simplified to standardized, clear batches of work that need to be made ready.

Increased common understanding: Common understanding is considered the 8th flow added to Koskela's 7 flows in construction (Pasquire, 2012). Common understanding is the result of engaging team members with a purpose. Engagement without meaning results in confusion. Takt time planning provides the opportunity for the entire production team, from detailers to foremen in the field, to develop a common understanding on the overall production strategy. In the field, a set Takt time provides workers with a daily goal. This enables a minimum daily calculation of output to stay on track, because the Takt time planning process already planned the production system around specific rates. In addition to the daily goal, Takt time adds purpose to the work performed, and provides workers with a clear vision of where they will be working next. For detailers, a common understanding of the production strategy enables them to design for Takt time, not just constructability and coordination.

Increased urgency for Make Ready work: Takt time increases the urgency for Make Ready work because failure to complete it will immediately affect the activities in the sequence.

Reduces scope of pull planning: The sequences of work through areas planned to Takt times are generalized, so the scope of work that needs to be pull planned is reduced to "one-off" pieces (e.g., operating rooms, imaging rooms, kitchen areas, etc.).

Targeted optimization: Takt time planning identifies the different activity durations to set the overall Takt time that every activity can reliably meet; thus, the Takt time is always subject to the slowest duration. From a production leveling perspective, improving the slowest trade activity would have the greatest benefit to improving the total duration for the entire phase of work.

Identifying "schedule noise" versus true "schedule variance:" Takt time plans can separate scheduled task variances in the commitment plan into "schedule noise" and "schedule variance." Schedule noise is defined as the temporal movement of a task within a given Takt time sequence that does not affect the completion of work within the Takt time sequence. Schedule variance is defined as the temporal movement of a task within a given Takt time sequence that shifts into another Takt time sequence. If a task moves into another Takt time sequence, then it conflicts with another trade activity and requires communication to either a) work out the conflict in the field without affecting the incoming trade (known as a soft conflict), or b) a replanning of the work because the current schedule will result in a delay of work for the incoming trade (known as a hard conflict). Figure 2-22 shows an example of work for a given activity divided into smaller tasks, represented as bars. A few tasks may shift around and create "noise," but only one task requires the production team to communicate and actively solve the problem.

Two outcomes result from discerning between schedule noise and variance. The first outcome is that it reduces stress on the general contractor, for the discernment reduces micro-management and a waste of resources on solving small schedule changes that do not actually affect the schedule. The schedule noise still needs to be managed by the trade foreman and crew responsible for the work, however. The second outcome is that Takt time planning creates a new perspective on PPC metrics. Takt time planning prefers a PPC metric that measures the handoff of work at the correct interval, instead of a PPC metric that captures the daily fluctuations in the schedule.

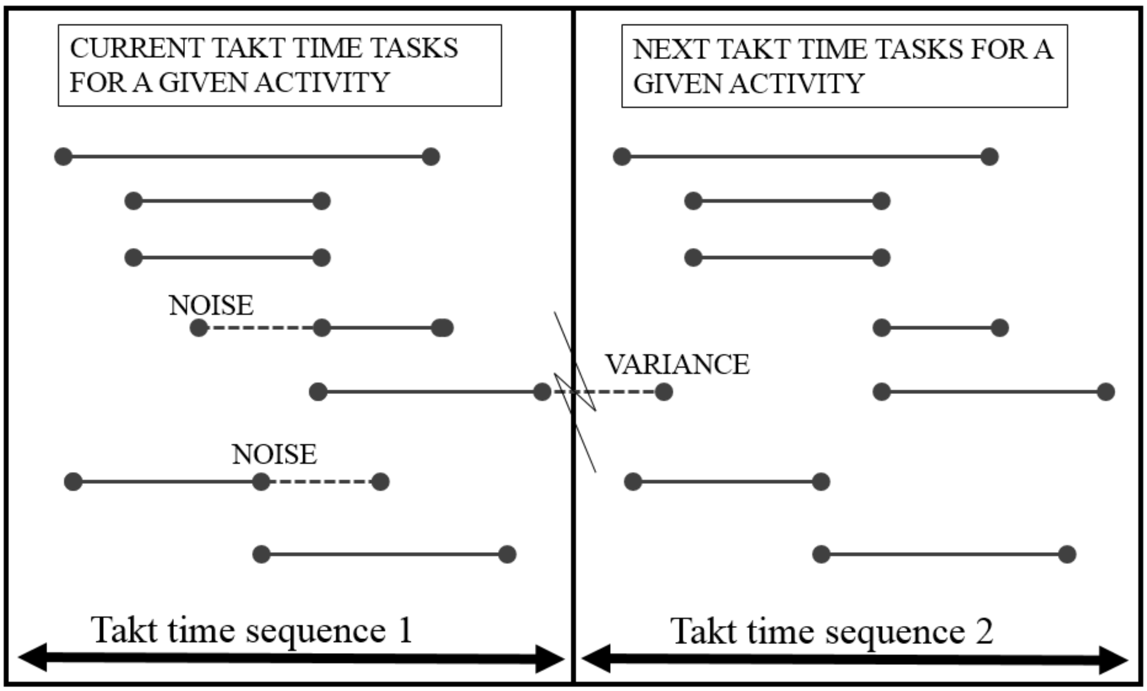


Figure 2-22 – Scheduling "noise" versus "variation" (the bars represent the start and finish of smaller tasks that make up a Takt time activity)

2.6 DISCUSSION

Lauri Koskela's research provides context for the contribution of Takt time planning research. In construction, Takt time planning is a method based on the principle of continuous flow in the TFV view of production (Figure 2-23). Further development of the method is necessary because current practice lacks a method for developing continuous work flow, unless the work is repetitive, and even then, the repeated activities may be unbalanced. Furthermore, owners consistently demand construction projects to be delivered at faster rates and lower costs.

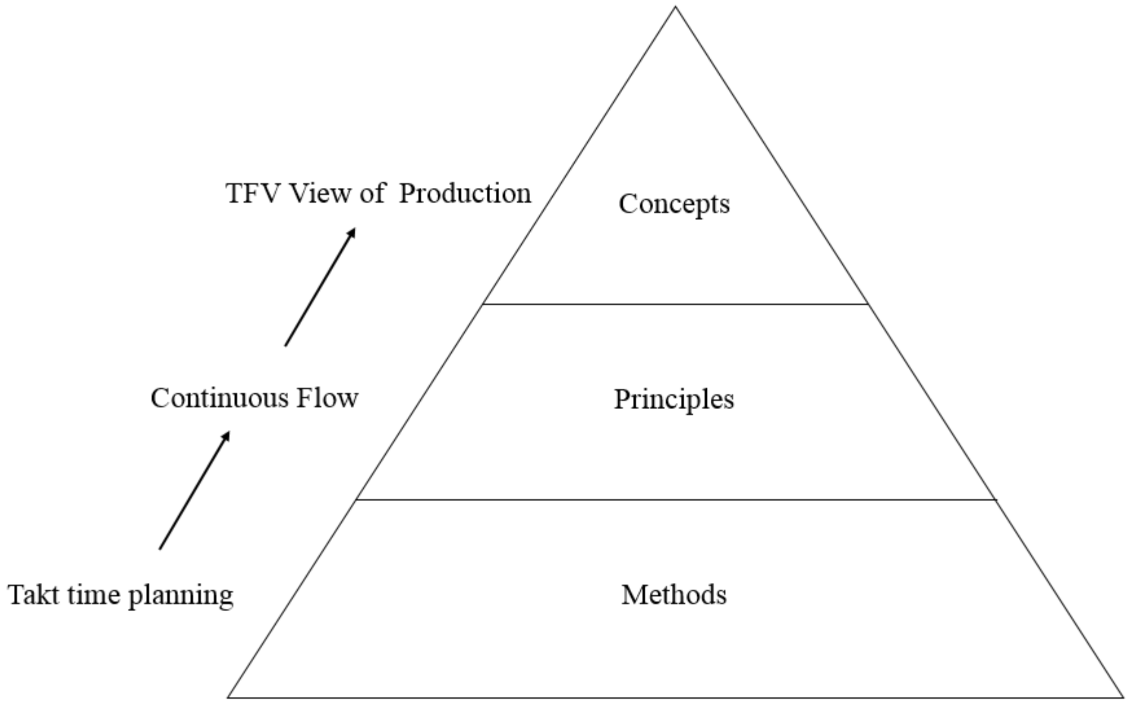


Figure 2-23 –Takt time planning in the context of Koskela's perspective on practical methods (Koskela, 2000)

From the previous sub sections, it is clear that there has been research effort into including space as a resource in the schedule, and therefore, produce schedules that are more effective. Figure 2-24 shows how Takt time planning connects with the different ideas and research topics presented. This dissertation situates Takt time planning in this context as a new area of research related to location-based planning, the Last Planner System, and TFV theory.

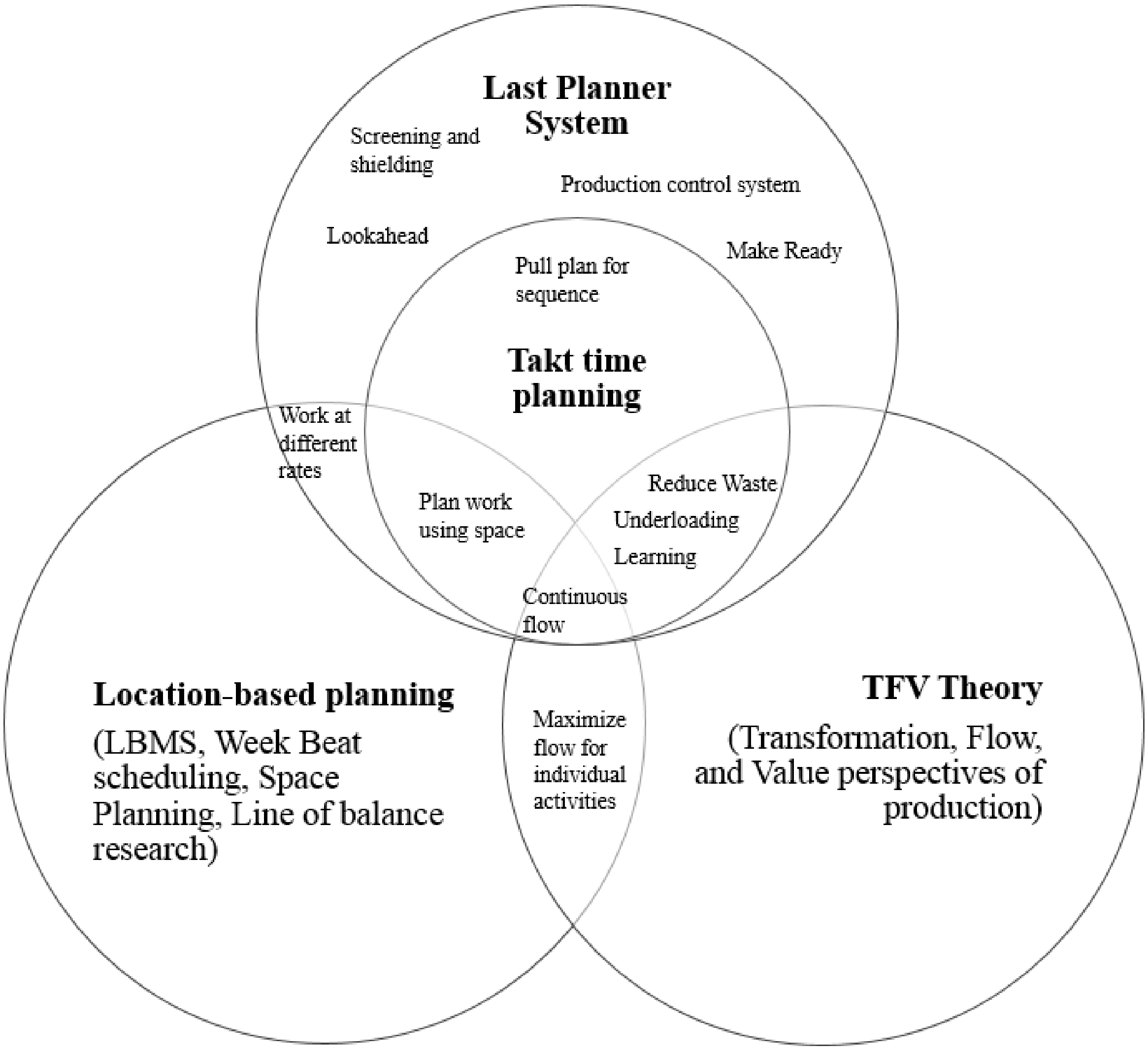


Figure 2-24 – Research context of Takt time planning

While a production schedule developed from Takt time planning may resemble other work structuring methods that use a Line of balance schedule, there is one critical difference. In Takt time planning, crews move through zones at constant rates; the zones and the rates are both parameters to adjust. In a production system where Line of balance schedules are used, the areas are not necessarily structured to be moved through at a standard rate; instead, the crew sizes are kept constant and the work is primarily scheduled for continuous use. This trade-off between crew size continuity versus standardized handoffs of work zones is a key difference between Takt time planning and other location-based planning methods. Takt time planning aims to maintain resource use when possible, but also attempt to create a global optimal solution for the project production system.

Scheduling using CPM, LBMS, Week-beat scheduling, or Takt time planning all can be thought of as work structuring methods, as they provide answers (intentionally or not) to the questions of work structuring. Table 2-1 focuses on the similarities and differences between

CPM, LBMS, Week-beat scheduling, and Takt time planning regarding zone definition, activity durations, activity sequences, use of buffers, and resource utilization. From the table, Takt time planning and Week-beat scheduling are most similar, but Takt time planning does not prescribe universal activity durations, the amount of capacity buffer, or 100% resource utilization.

	CPM (Jackson 2010)	LBMS (Seppanen 2009)	Week-beat scheduling (Court 2009)	Takt time planning
Zone definition	Not defined, may be inherited from how the structure is split a part in design or previous phase	Unclear how zones may or may not be defined for leveling purposes	Zones defined approximately around "a week's-worth" of work	Defined to level the installation times required for every trade in every zone
Activity durations	Defined by 1) Work method assumed, duration a function of quantity take-off and a production rate or 2) Assumed duration based on an estimate	Work method assumed, duration a function of quantity take-off and a production rate	Assigned a week, resource load the project for each area to obtain that activity duration	Defined by the chosen work methods, crew sizes, and zones
Activity sequencing	Assumed activity sequencing, may use varying network logic (Start-to-start, finish-to-start, start-to-finish, finish-to-finish, delays, etc.	Assumed activity sequencing, may use varying network logic (Start-to-start, finish-to-start, start-to-finish, finish-to-finish, delays, etc.)	Utilized finish-to-start relationships in a sequence agreed upon by those performing the work	Designed based on the feedback from the people performing the work
Buffering	Time buffers appear for certain activities not on critical path due to float calculations	Plan time buffers to prevent different crews performing activities from interfering with other crews and their activities	Buffer with a fixed 25% extra capacity	Use capacity buffers to account for variation

Resource utilization	Assume full resource utilization. May resource load the schedule to identify how resources are used to improve upon continuous use of resources	Plan for full resource utilization	Plan for 80% utilization (i.e., underloading) of resources to improve reliability	Plan for underloading to improve reliability

Table 2-1 – Similarities and differences between work structuring methods

2.7 CONCLUSION

Production theory is a blend of craft, scientific, and practical knowledge. Developing methods to apply principles based on a unified production theory improves practice and helps develop the theory further. Takt time planning is a method that supports the Lean/TFV principle of continuous flow. This chapter covered several areas of location-based planning research, and specifically expanded upon Line of balance scheduling to illustrate some of the workflow challenges with crews moving at different rates through zones. This work focuses on Takt time planning as a method, and may refer to research in other location-based planning topics; nevertheless, the primary contribution of this research is to further the development of a method that produces continuous flow.

CHAPTER 3 RESEARCH METHOD

3.1.1 Introduction

This research applies diverse methods to answer the established questions and fulfill the objective. This study applies the case study research method to gather data, and an action-based approach by directly affecting the production system on a project and evaluating the change. This approach is based on design science research, in which an artifact is created, implemented, and evaluated with the goal of creating generalized knowledge. In addition, discrete event simulation is used to compare the effects of structuring work around specific Takt times and zone configurations with other work structuring methods. Each method was selected based on their suitability to help answer the research questions. The case studies were based on multiple criteria described below. This section begins with an overview of each method, then describes how the methods were synthesized to form the research method, and concludes with the method used for selecting case studies.

3.1.2 Design Science

March and Smith (1995) list three modes for producing knowledge. Natural science produces theories that explain the causal relationships in the world. Social science describes human behavior and other social phenomena. Design science produces knowledge that is primarily prescriptive. While similar to case study research, design science is different because the aim of case study research is not necessarily to prescribe. The benefits of using design science are that it creates practical solutions, generates new theory, and narrows the gap between practice and research.

March and Smith (1995) describe four sequential activities for conducting design science research:

(1) Building the artifact – constructing an artifact to fit a specific purpose.

(2) Evaluating the artifact – How well does it work?

(3) Theorizing – Explain why does it work or not work?

(4) Justifying – What evidence is there to indicate this conclusion?

Building the artifact starts with descriptive research in order to understand the environment and the problem. Evaluating the performance of the artifact is based on a specific environment and builds further understanding of the problem, generates knowledge about how to improve the solution, and also helps to produce more generalized knowledge of the system. One risk in design science is overgeneralizing the benefits of an artifact; thus, it is important to communicate the specific environment in which the artifact was tested. Testing the artifact in varying environments is one way to mitigate this risk. Building and evaluating it are practice-focused, whereas theorizing and justifying are theory-focused.

Researchers using design science must consider its cyclical nature and context. The cyclical nature of design science changes artifacts over time due to increased problem understanding and knowledge gained from testing the artifact. Understanding the environmental context of an artifact is important because it may solve one practical problem in one environment well, but have unforeseen consequences when it is introduced into another. Related to both considerations is the level of development and maturity of an artifact. A first iteration artifact may undergo much more change than a mature artifact designed from one hundred iterations.

3.1.3 Action Research

Lewin (1946) used the term "action research" to describe the nature of his research methods in the paper "Action Research and Minority Problems." He states, "action research is a comparative research on the conditions and effects of various forms of social action, and research leading to social action." In production research, action research studies how changing the conditions of production affects production, leading to how changes in production systems may be designed. Lewin's describes his premise for using action research: "the diagnosis of problems does not suffice. It must be complemented with experimental studies of the various techniques of change." In other words, researchers need to identify and solve problems.

Action research requires that the researcher is an active participant in the study (Jarvinen 2007). Thus, the researcher becomes part of a five-step cyclical process of: (1) problem diagnosing; (2) solution planning; (3) acting; (4) evaluating; and (5) learning (Susman and Evered, 1978). This cycle is similar to the four-step Shewhart/Deming cycle (Deming, 1986). Action research is necessary in construction when a project implements a method that is new, untested, or with which the team is unfamiliar (though team members may be familiar with the theory). Another reason for using action research in construction is that the lab environment is essentially the construction site.

3.1.4 Case Study Research

Case study research may be exploratory, descriptive, or explanatory (Yin, 2009) and helps to form generalizations, while including direct observations and interviews other research methods may omit. Yin recommends using a case study when, "a 'how' or 'why' question is being asked about a contemporary set of events over which the investigator has little or no control." The definition of case study research by Yin is, "an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are clearly not evident."

Researchers should test the reliability of observations between multiple sources in case study research (Yin, 2009). If the sources converge and corroborate each other, the observations are more credible.

Data obtained from case study research takes several forms. This research used in-person interviews (formal and informal), schedule data, annotated design documents from projects, meeting notes, as-built information, construction logs, and surveys to gather data.

3.1.4.1 Research Method and Structure for Case Studies

The three selected case studies follow a similar format. The researcher detailed the development of the Takt time plans for different project phases, presented the results, and discussed the lessons learned on the project with respect to Takt time planning. The results come from the schedule data, Weekly Work Plan data, and project cost information.

Each case study will have the following structure:

1. An introduction presenting the project characteristics (size, location, contract value, etc.) and which phases of Takt time planning were applied

2. Case study timeline listing (if known) when the construction started/finished, when the Takt time planning process began, and when the phases of Takt time planning began
3. Detailed development of the Takt time plan
4. Results
5. Discussion of results and observations from the case study
6. Case study conclusion

The case studies are compared and discussed further in Chapter 10.

3.1.4.2 Research Method for Scheduling Data

Actual data for starts and finishes was obtained from the Weekly Work Plan data. Activities not identified in the schedule were ignored. The research used schedules from either the initial contract schedules adjusted to the start date of the phase, or the schedule provided by the general contractor. If the data came from the general contractor's schedule, it was labeled by the name of the general contractor. The initial contract activity start dates to the phase were adjusted during the project, and were done if the phase was delayed by a previous phase. If an activity disappeared from the Weekly Work Plan before the start date, but it appeared in previous Weekly Work Plans in the Lookahead, it was assumed to have completed early if the activities preceding it were shown in the plan. Daily work reports were also analyzed to confirm Weekly Work Plan days. If an activity was shown as complete, its finish date was updated to reflect the early finish, even if the Weekly Work Plan showed it finishing in the following week.

An example of the data is shown in Figure 3-1. Though this data does not show a complete picture of how a project was executed, it does visually identify activities not executed per the plan. The next step is to inquire and understand why the activities did not follow the plan, learn from the data, and improve planning on future projects.

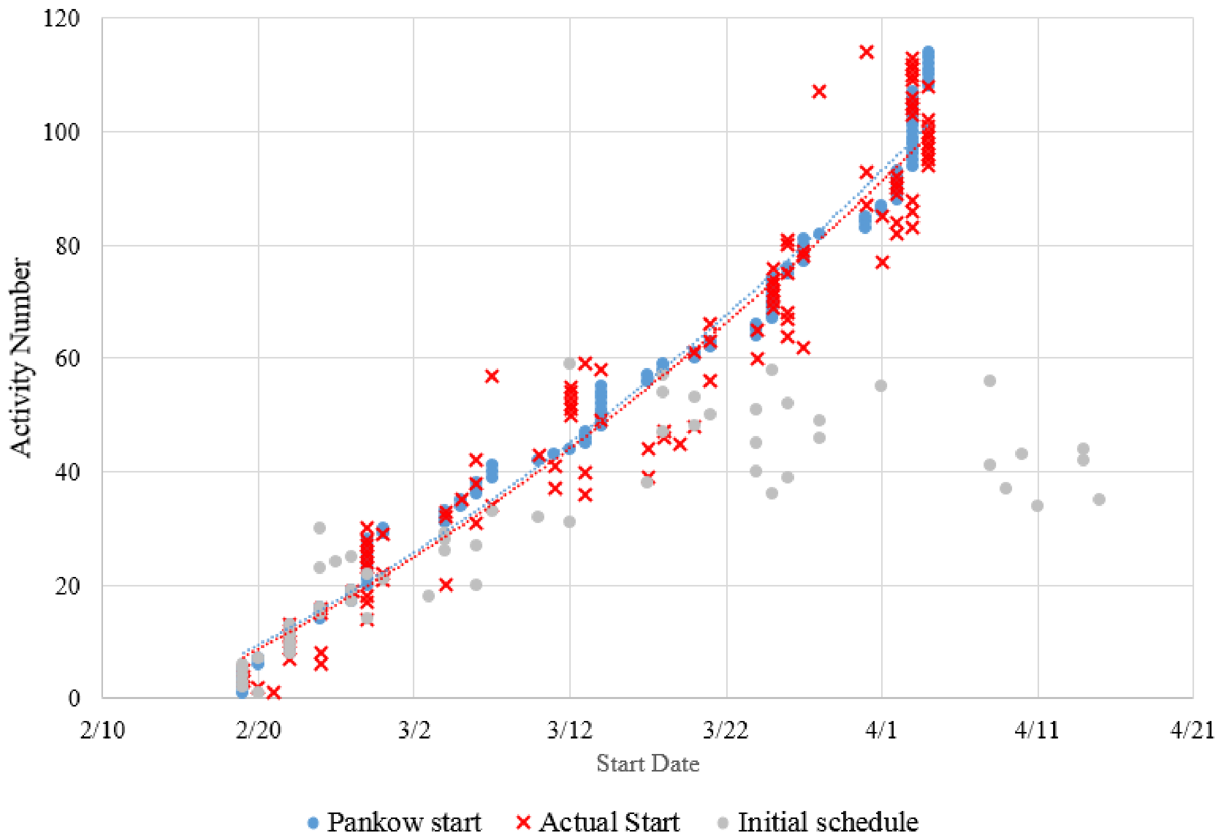


Figure 3-1 – Sample schedule data comparing start dates

This type of schedule analysis contains limitations and potential sources of bias. There is no automatic discrimination between important and normal activities; thus, all activities are assumed equal. Further analysis is required on identifying activities starting earlier or later, what those activities are, when they finished, and the consequences. Another counter argument to using this type of data is that it is easy for project teams to start activities, even if the previous activity is not finished (e.g., the handoff was not made well). However, if done in excess, the construction schedule will eventually get delayed if the handoffs need to be made in the way the team planned them. In addition, if the team is following the Last Planner System and only committed to work that is ready (i.e., the handoff is met), the starts will accurately depict how a team executed a plan. As such, assessing schedule starts is a good indicator combined with Weekly Work Plan data, and project cost data to assess if a project is executing to plan.

The inspiration for using this schedule data came from popular use in scheduling claim disputes. Schedule data can reveal projects that did or did not execute to plan. In addition, the data is compared with the Weekly Work Plan data, which is committed to, and planned by individuals closest to the execution of the work. Thus, if the initial Takt time plan aligns with the way the work is actually executed, the team uses the Last Planner System to track the activities in the Takt time plan, and the project is finishing on time and at or under budget, this indicates that the Takt time planning approach likely helps the project.

3.1.5 PROJECT SELECTION

While project selection for research was somewhat opportunistic, it was not random. Each of the cases was required to meet the following criteria:

- Needed to be physically accessible (i.e., the researcher can get to the project on their own accord).
- The construction phases studied needed to finish within the timeframe of the research
- Require a minimum buy-in from the team to participate in the research (i.e., they will let us on the site, talk to us, and implement the Takt time planning method).
- Be comparable with the other projects (e.g., contain an interior phase of construction).

With that said, the criteria still left a variety of potential projects to observe. The common criteria serve the purposes of identifying differences in projects with similar work contents and reflected the researcher's familiarity with the work contents. The temporal constraint favored 'smaller' projects, though the researcher observed Takt time planning on larger scopes of work not covered in this research. A benefit to smaller projects is rapid learning and iteration of the method. The shorter schedules on smaller projects also allow for measurement of project success (A large project may complete well outside the research schedule). Smaller projects are also easier to influence, as there are fewer people who need to "buy in" to the idea of Takt time planning.

Despite its temporal disadvantages, large projects have research advantages over smaller projects. The first is that complexity, communication, and logistics challenges come with increased project scale, and results in proportionally greater consequences if processes like managing deliveries or coordinating material logistics in the space are not tightly controlled. These issues make positive or negative changes in planning methods more obvious to measure and study. Second, large projects are not as likely to suffer from what can simply be defined as "super" super-intendent syndrome, where a good superintendent can effectively manage the project site due to its scale. As such, new work structuring methods may appear more successful than they are, due to the superintendent's exceptional work. However, these advantages cannot outweigh the suitability of smaller projects as a better 'laboratory' for new ideas and alternatives.

Table 3-1 describes different characteristics of the projects with which the researcher tested Takt time planning. As shown in the below table, Takt time planning was tested at varying levels of buy-in, contract value, modelling detail, familiarity with lean construction practices, levels of staffing, and different types of contract structures.

	Case Study 1	Case Study 2	Case Study 3
Project Size	\$3,500,000 7,000 ft^2	\$16,100,000 19,000 ft^2	\$6,600,000 14,000 ft^2
IFOA	Yes	Yes	No (GMP)
Superintendent buy-in	Yes	No	Yes
Team buy-in (including an engaged owner)	High	Low	Medium
BIM	Yes	Partial	No
Project staff allocated an engineer for TTP?	Yes	No	No
Balanced TTP		Yes	
Visual controls (for at least a portion of the work)	Yes (checked daily)	Yes (checked weekly)	Yes (partially in finishes)
Project members familiar with LPS	Yes	Yes	No
OSHPD 1 Code Compliant Project?	No	Yes	No

Table 3-1 – Overview of case study project characteristics

In general, the characteristics were highlighted because they all appear to affect the implementation of Takt time planning.

Contract Value – Contract value is an indicator of project size. As discussed in 3.1.5, larger projects may have different challenges than smaller projects.

IFOA (Yes or no) – The contract structure affects the incentives of the different contracting parties. IFOA is short for Integrated Form of Agreement (Lichtig, 2006). An IFOA aims to shift risk between parties by creating a contract structure in which risks and rewards of the project are shared between the owner, designers, and contractors. Thus, IFOA incentivizes optimization of the project. Testing Takt time planning in environments with and without strong incentives to locally optimize should give a better indication of where and how Takt time planning can be applied.

Superintendent buy-in – Superintendent buy-in is purposefully singled out to begin to assess its importance in implementing and executing Takt time planning. Buy-in from the superintendent is confirmed by their behavior on site by answering the following questions: Does he support the Takt time plan? Does he use the plan? Does he have his own schedule separate from the Takt time plan? Does he schedule the subcontractors in areas of the Takt time plan?

Team buy-in – All preliminary work indicates that high team buy-in is critical to the success of Takt time planning. Thus, it is important to differentiate projects with and without a high team buy-in. The team members considered here are the subcontractor foremen and project managers, owner, and general contractor project members. Also included is buy-in to using the Last Planner System for help with production control support. This was a subjective assessment supported by informal interviews collected on site.

BIM modeled (Yes, no, partial) – 'Partial BIM' was defined by examining the current state of BIM on a project. If the BIM was missing large scopes of work, like an MEP system, foundation rebar, or stud framing, the characteristic was defined as 'partial BIM'.

Project allocated an engineer for Takt Time Planning – This is a simple yes-or-no question, and reflects whether or not the project team allocated project engineering resources to help facilitate Takt time planning.

Strict Takt time plan – A strict Takt time plan is defined as a sequence of activities following the same Takt time, sequence through the zones, and trade sequence (i.e., the main variables affecting the sequence duration are simply the Takt time, number of sequences, and number of zones).

Visual controls – Visual controls are visual plans communicating the plan directly in the field, which helps to create transparency and decentralize control of the schedule.

Members experienced with Last Planner System – This is a general assessment of whether the team has used the Last Planner System in the past, and what their level of understanding was at the project outset. Familiarity with the Last Planner System can influence the implementation of Takt time planning (the Takt time it self, the zone size, the visual control implementation, etc.).

OSPHD 1 Code Compliant Project – OSHPD 1 Code compliant projects demand a significantly greater level of quality control in design and construction, so it is important to identify which projects need to meet this requirement. On OSPHD 1 projects, inspectors need to examine every component and ensure that it was installed per the plans with very little flexibility in installing anything that is not per the plans. This requires detailed inspection and documentation processes. Thus, requiring design to be near perfectly constructible, for any additional design that affects structural integrity must go through a lengthy approval process that can take 90 days in some instances. As such, OSPHD projects may have 'Lookahead' requirements for activities to maintain the project schedule.

3.1.6 SIMULATION MODELING

Simulation modeling is an art and a science, as modeling requires an artistic, subjective approach, and the confirmation of the model requires objectivity (Mihram, 1976). Simulation methods help to develop an understanding of physical systems. Mihram identified six steps to simulation modeling:

1. Setting model goals
2. System analysis
3. Model synthesis
4. Model revision
5. Model confirmation

6. Scientific contribution

Simulation modeling has several advantages over experimentation through action research. First, it provides the ability to study the impact of variation. Second, simulation modeling provides a method to predict performance. Third, simulations can repeatedly provide results on a variety of experiments quickly. Fourth, simulations are virtual; thus, companies, projects, and people are not directly affected if the results are negative.

This research used discrete event simulation for modelling how different work structuring methods affect project outcomes in time and cost. In this case, the researcher modelled a production system on site with crews. The state variables to model are not continuous, and the system itself can be modelled stochastically; thus, it is a good candidate for discrete event simulation (Dooley, 2002). The research also considered an agent-based simulation and system dynamics simulation, but these options did not fit the goal and questions of the intended simulation.

3.1.7 Research Tools Required

This research used software-based tools. Vico software was used for Line of balance scheduling (Vico, 2009). Excel (2013) was used for production tracking, Weekly Work Planning, data analysis, creating visual schedules, and calculating Takt time scenarios for strict cases of Takt time use. Microsoft Project (2013) was also necessary for scheduling on some projects. Adobe Illustrator (2015) and Bluebeam (2015) were used for some illustrations and annotating PDFs of floor plans. Navisworks (2011) was used for accessing BIM models. Vernox Pulse (2015) was used for managing a Weekly Work Plan on one case study. Stroboscope was used for the simulation. All of this software was available free to students at UC Berkeley, or could be made available through the projects.

Implementing visual production tracking in the field required a board (placed in the field) for colored up floor plans. A magnetic white board seemed to be the most effective type of board, but simple tacks into a sheet of plywood also met the requirements. As an aside, implementing visual production tracking in the field also required daily project support to ensure that the prints on the board were up to date.

3.1.8 Method Synthesis and Conclusion

This mixed research method was selected because of the nature of construction projects. With a variety of systems networked together on a project, the environment becomes incredibly complex to conduct research and control. However, it is still possible to test hypotheses and develop knowledge through experimentation, iteration, and patience.

Overall, the research was design-oriented. The three case studies provided an opportunity to iterate upon, understand, test, and develop a work structuring method under a wide range of project characteristics. The background literature research combined with the initial descriptive research presented in the appendices (Frandson et al., 2013) provided a good foundation and an artifact (Takt time planning) to test. Each case study required an active approach because the method is new and practitioners needed guidance with implementation. The effectiveness of the Takt time planning was validated with the cost and schedule data from each case study. Simulation is required because the case studies indicate that some factors are likely critical to the decision to trade between capacity and time buffers. A benefit to simulation is that it provides a relatively “harm free” way of trading between buffers.

Below is a summary of how each question will be answered in the dissertation.

Question 1: What does Takt time planning in construction look like?

This question was answered through action research, iteration across the different case studies, and simulation.

Question 1.1: What are the characteristics of flow in construction?

This question was answered from the case study observations.

Question 1.2: When should construction aim for flow?

This question was answered from the case study observations.

Question 1.3: Under what conditions is there a benefit to scheduling work while underloading?

This question was answered through simulation and was inspired by observations through the case study findings.

Question 1.4: How can using Takt time planning as a work structuring method improve decision making for project execution?

A mix of simulation and action-based research helped to answer this question. Action-based research provided examples of how Takt time planning impacted decision making; simulation validated whether the decision was an improvement for the project.

Question 2: What barriers exist to designing continuous workflow of activities in construction?

Case study research helped to answer this question by providing the specific instances of barriers to designing continuous flow. Simulation helped to quantify the impact certain barriers have to designing continuous flow.

Question 2.1: What types of variation may be absorbed with capacity?

Observations through action research answered this question.

Question 2.2: How reliable are Takt time plans?

This question was answered with the schedule data from the different case studies.

Question: 2.3: What are the consequences of designing a production system around different zone sizes?

This question was answered through case study observations.

Question 3: What are the costs and benefits to using Takt time planning?

Project schedule and financial data combined with simulation helped to answer this question.

CHAPTER 4 FIRST INSTANTIATION OF TAKT TIME PLANNING

4.1 INTRODUCTION

This chapter introduces the first instance of Takt time planning the case studies iterate as described by Frandson et al., 2013. The first author conducted descriptive research on a project after the exterior phase was completed and did not actively participate in Takt time planning. This chapter will also compare this instance with the use of Takt time planning for interiors of the same project described in Linnik et al., 2013. Similar to a case study, the chapter introduces the project characteristics, followed by the process for Takt time planning, the results, and a discussion on the lessons learned/open questions for Takt time planning.

The first instance of Takt time planning focused on planning the installation of the exterior cladding system and the interior build out of the Anderson Lucchetti Women's and Children's Center (WCC) in Sacramento, California. The WCC is a nine-story, 242-bed, 36,700 m^2 (395,000 ft^2) facility providing women's and pediatric care. The WCC was part of a multi-project, $735 million health care program (Boldt, 2012). The owner of the project was Sutter Health, a not-for-profit health care provider in Northern California. The architect was Ewing Cole Architects. The construction manager and general contractor was The Boldt Company.

4.2 TAKT TIME PLANNING PROCESS

Through experimentation, the production team identified seven steps for Takt time planning:

1. Identify phases to follow the Takt time plan (Linnik et al., 2013 mentions this phase; Frandson et al., 2013 does not)
2. Gather information
3. Define areas of work (zones)
4. Understand the trade sequence
5. Understand the individual trade durations
6. Balance the workflow
7. Establish the production plan

Step 1 – Identify phases to follow the Takt time plan: This phase identifies the trades included in the phase and an area structure, called "takt areas" through which the trades will work. Work excluded from these phases will be considered workable backlog.

Step 2 - Gather Information: Trade by trade, identifies the work to be done, and where. One method for gathering such information is to have those who understand the details of the work (e.g., foremen) use a colored marker to highlight a floor plan showing the work they can do, e.g., in one day. This process results in 'color-ups' (Figure 4-1 and 4.2).

Color-ups differ from quantity take-offs (which describe a more general nature of the work to be performed, and in what amount in order to support estimating and procurement), as they require consideration of how the work will be performed, by whom, where, and in what sequence. Planners can work with trades by asking questions such as 'If you could start anywhere on day one, where would you begin?' Each trade uses a different color for each day to mark up their scope of work on the floor plans. This process helps to identify the preferred durations and individual trade's production plans. These color-ups also identify the natural breaks in the work (e.g., at fire-rated walls) and areas that require a break (e.g., joints). In addition, color-ups identify the preferred sequence of work (i.e., work from the shaft out, left to right, etc.).

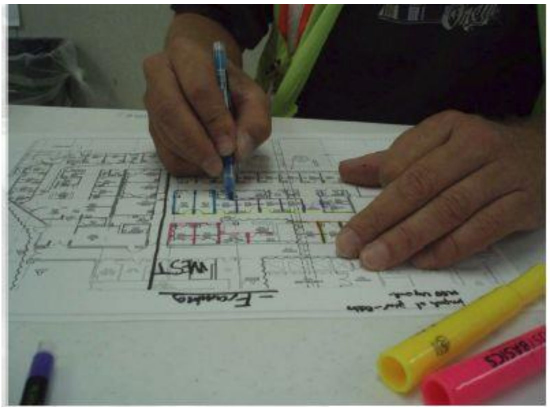


Figure 4-1 – Creating a color-up

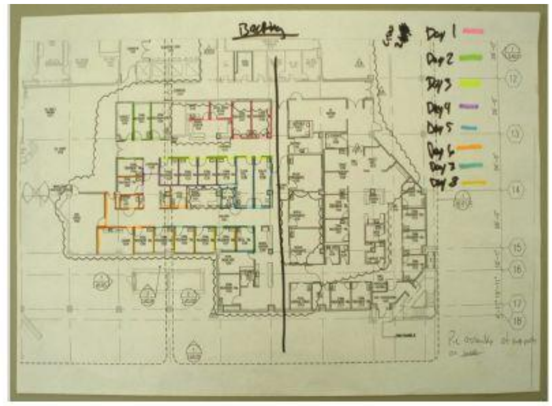


Figure 4-2 – Example of a color-up

Step 3 - Define Zones: Takt time is the time a trade is afforded to complete their work in a zone. Accordingly, zones are areas to which trades will be controlled. The ideal zones are batches of work that take the same amount of time for each trade to complete. Initial zones are created from the information obtained in the previous phase. At this point, the Takt time is still undefined, as there is still insufficient information to establish one.

Ideally, BIM and the zones can be aligned, but this is currently a challenge, because the model may be less developed than the detail required for individual trades to establish production rates.

Step 4 - Understand the Trade Sequence: Understanding the trade sequence requires trade coordination meetings. The general sequence of trades and approximate durations is obtained from pull planning through a single area. Who needs to work through a zone, when they need to work with respect to the other trades, and how many passes each trade will require are all vital to understand in order to continue with Takt time planning process.

Step 5 - Balance the Workflow: The combination of established zones, approximate durations, and known sequence information allows for the balancing of workflow. The production planning concerns at this phase are: What trade activities need to slow down? What activities need to go faster (i.e., which trade is the bottleneck)? How can zones be further adjusted to balance out the workflow? In the interior instance, the team balanced the zones around the bottleneck trade to improve workflow.

Step 6 - Understand the Individual Trade Durations: Balancing the workflow requires first-run studies to establish more accurate durations for gauging the work in each zone. First-run studies are critical in identifying the soundness of the design and the details provided.

Obtaining workflow balance does not occur immediately. Rather, it becomes established through a gradual, continuously-improving process that establishes the Takt time.

Step 7 - Establish the production plan: The rate at which the activities proceed through the zones with a balanced workflow is the Takt time for the set of activities. Using this production rate, foremen managing the activities can break the work down into smaller time increments. The purpose of managing to a time interval smaller than the Takt time is to track progress as work proceeds in order to forecast when the Takt time will likely not be met. Corrective action can then be taken right away, well before the Takt is exceeded.

The established production plan also sets the pace for design, coordination, material fabrication, and material deliveries.

Roles and Responsibilities

The general contractor managed the production plan with weekly work planning meetings. A general superintendent and a project engineer were dedicated to the exterior work. The teams were formed as an Integrated Project Delivery team. The superintendent acted as a leader and facilitator for all of the trade superintendents. The general superintendent made the final decisions, and the project engineer was responsible for updating and checking the plans. The team members acknowledged that this framework required much more coordination than the traditional method of building an exterior. The general superintendent was also involved with organizing the daily production plans that were filled out online, and ensured that they were updated and reliable. Overall, the superintendents were identified as the cornerstone to the entire production planning process.

Interior Takt time planning process

The steps identified in Linnik et al. (2013) are similar to those in the exterior phase, but the assumptions made by the team were different and worthy of discussion. In step 1, a tentative area structure, called "takt areas," was established by the general contractor. The general sequence was pull planned. When balancing the work flow, the Takt time was set at five days. The two counter-measures for maintaining the five-day Takt time were to: (1) design the operations, and/or (2) adjust crew sizes. The areas were also adjusted to accommodate the bottleneck trade during the drywall phase: the drywall trade partner.

The assumptions made in the interiors are part of a notably different process than the one described for the exteriors. The exterior Takt time planning process was more of a "bottom-up" construction of the production schedule than the interior Takt time planning process. The team went into planning the phase without a notion of the Takt time or areas structure, while the interior framing phase started when the general contractor proposed an area structure and a set Takt time to which the team would plan.

4.3 Results

The results from Takt time planning at the WCC were impressive. The initial schedule set a partial completion of the exteriors after 11 months. With the four-day Takt time schedule, the team completely built out the exteriors in 5.5 months. The team missed the first three Takts, then made the rest. The interior team hit 100% of Takts in the framing phase, and 94% in the drywall phase (Linnik et al., 2013).

The team made other observations regarding Takt time. The ability to look ahead at upcoming work improved, partly due to the simplicity in the schedule. This also translated to a simpler procurement schedule, and a clearer understanding of when and what material would be required on site every week. The project team also perceived more pressure than a typical project for disciplined processes of constraint identification and constraint removal, for if the team was not removing constraints effectively, the Takt time plan would break down. Linnik et al. also observed that Takt time planning enabled bottleneck and non-bottleneck trades to improve. Linnik et al. (2013) was also the first case where there was no segregation between non-repetitive and repetitive work in the Takt time plan. This is significant because it indicates that Takt time planning could be used on non-repetitive projects, expanding the boundaries regarding where Takt time planning may be applicable.

4.4 Lessons Learned and Open Questions

The two case studies provided a number of lessons learned and open questions. First, it is interesting that Takt time planning could exist on a single project, but its use was very different, depending on where it was applied. There appeared to be no clear understanding between the variables of Takt time and the zones (Takt areas) through which crews work, but these appear to be central to Takt time planning. Related to Takt time and zones is the idea of workable backlog, and how this may be used on a project to balance the variation in required crew sizes between zones. Finally, Linnik et al. (2013) commented that the overall productivity impact and project costs were still unknown.

4.5 Conclusion

The combination of the success of Takt time planning at WCC and the lack of understanding of how it really worked made it a motivating research topic to pursue. The two cases on the project used Takt time planning in different ways, with different assumptions. The success of the "bottom up" construction of the plan in the exterior phase required further testing and inquiry. Testing how Takt time planning works (or doesn't) with seemingly non-repetitive work also required more understanding. In all, the case studies revealed how a collaborative team could work with a number of variables relating to work structuring (zones, pace, work sequence, etc.) to create a production schedule to which an entire project team could align.

CHAPTER 5 CASE STUDY 1: MILLS URGENT CARE CENTER

5.1 INTRODUCTION

This chapter presents a case study of Takt time planning developed for the construction of the interiors (from the release of a demolished interior space through finishes) of the Mills Urgent Care Center (Mills) project in San Mateo, California. Given its location and building type, the project had to meet among various other building codes, California's earthquake design codes including the requirements of the Office of Statewide Health Planning and Development (OSHPD). Mills was a $3,500,000, one-story, 7,000 ft^2 (650 m^2) gut and remodel in an existing hospital.

The owner of the project is Sutter Health, a not-for-profit regional health care provider in California. The architect was BFHL Architects. The construction manager and general contractor was Charles Pankow Builders. The project used an Integrated Form of Agreement contract with shared risk and rewards for the owner, and 11 major design and trade partners, with hard bid subs under the general contractor.

Development of a Takt time plan for the interior trade activities on this project was decided by the general contractor and trade partners (drywall, mechanical, plumbing, and electrical trades). The researcher's adviser made a request to the owner on the project and introduced the adviser to the team. She made the case to use Takt time on the project and they bought into the idea. At that time, the team was also considering hiring a lean consultant. The rationale for using Takt time planning was to plan the work that normally proceeded at different rates, and experiment to determine whether the work could be planned with better work flow. The project team created Takt time plans for the overhead MEP rough-in phase, inwall MEP rough-in phase, and finishes phase of construction. The team executed the overhead and inwall Takt time plans, but did not use the Takt time plan for the finishes work because the subcontractors for this phase were not engaged early enough in the project, the team did not trust the plan, and the steps to Takt time planning were not followed. In the following order, this chapter describes the Takt time planning process, results, and lessons learned from the case study.

5.2 CASE STUDY TIMELINE

Figure 5-1 presents the timeline of the case study. The owner, general contractor, and architect signed an Integrated Form of Agreement (IFOA) contract in June 2012. The remaining signers signed at a later date. In all, the 12 signers on the contract were the owner, general contractor, architect, civil engineer, structural engineer, mechanical engineer, electrical engineer, fire sprinkler contractor, mechanical contractor, plumbing contractor, drywall contractor, and electrical contractor. In May 2013, the Takt time planning research started with playing the Parade of Trades game with the project team, and informing the team members of the plan to use Takt time planning on the project. In the succeeding weeks, the researcher's advisor scheduled meetings with each trade partner to understand their individual requirements and work methods. In the context of the Last Planner System, this period of data collection preceded the Reverse Phase Schedule meetings that would later sequence the work. In September, the project had its final schedule, and construction began in December.

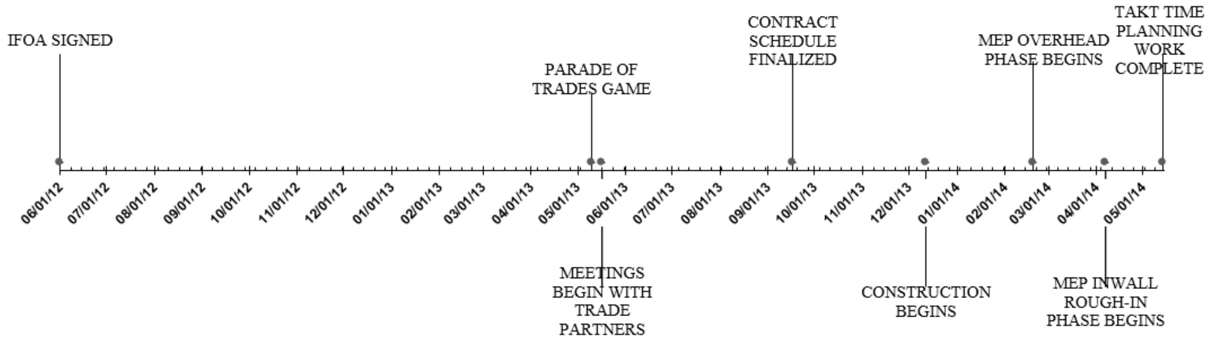


Figure 5-1 – Case study timeline

5.3 Takt Time Development for Overhead MEP Rough-in Phase

Takt time planning for the overhead MEP rough-in phase started with data collection. The researchers, superintendent, and project manager met for two hours with each of the trade partners involved in this phase. These trade partners were the drywall partner, the fire sprinkler partner, the piping and mechanical systems partner, the electrical partner, and the plumbing partner. The researchers asked each trade partner to come prepared to the meeting with plans printed out for their work. In each meeting, the trade partner marked up the scope of work and desired sequence on the plans.

In the overhead MEP rough-in phase, the drywall partner had work at the shaft walls that released work to the MEP trades. This work needed to start first, and the drywall partner also preferred to complete all his wall layout at this time. A benefit for the team to complete the wall layout first, was that it could help to reveal clashes between MEP components and walls before the walls were framed.

The fire sprinkler partner's desired workflow in this phase was to complete "full lines" of work (i.e., fire sprinklers are laid out in a grid to cover the entire space, so they preferred to complete a line of sprinkler heads at once). The fire sprinkler foreman also found that the final connections (i.e., "the drops") to the fire sprinkler heads, with the exception of a few locations, would have to be performed in the finishes phase because the fire sprinklers must drop into the center of the ceiling tiles. The fire sprinkler system still needed to remain operational during construction, so the team opted to use temporary heads connected high at the bottom of the deck above. Leaving their final connections off until the finishes phase is also beneficial to the other overhead MEP trades, because there are no live sprinkler drops to move components around during installation.

The piping and mechanical partner identified what they could do on each day of work, given their desired sequence, from the very beginning of the meeting (Figure 5-2 and Figure 5-3). This level of detail was helpful for planning the work and understanding what sort of zones and paces were feasible for them. It showed precisely how they wanted to work, and how much work they could perform in a day, given their preferred sequence and crew size. The sheet metal foreman was able to create a color-coded floor plan of the ductwork, as well as a desired sequence and the corresponding durations for each activity.

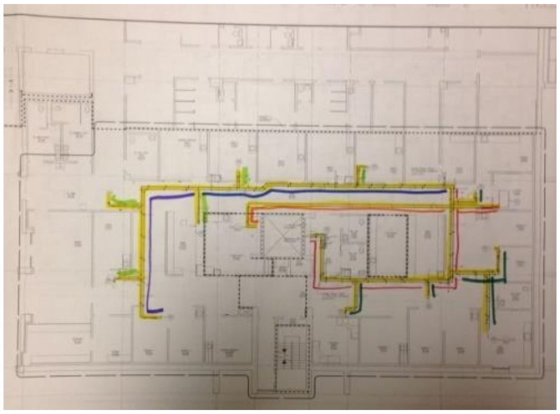


Figure 5-2 – Piping workflow

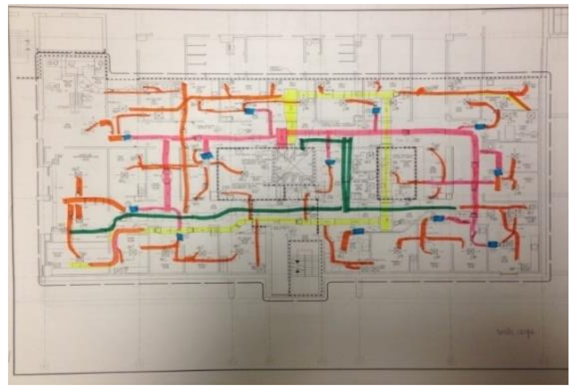


Figure 5-3 – Duct workflow

The electrical trade partner was represented by the owner and electrical superintendent on the project. The electrical superintendent divided their work into quadrants. Durations were calculated from a task list at a greater level of detail than the Master Schedule and the location of all of their overhead work was provided. While helpful for planning, this level of detail was not robust, because the crew sizes and durations were specific to the quadrants and could not be reduced and reconfigured into different zones. The resolution was low relative to the piping and mechanical information provided by the mechanical piping foreman, who had broken down their work daily and in much smaller sections. In addition, there was little detail about how the work would be performed in the area (e.g., does the electrician really need the whole space for the whole period, or will the quadrant be worked through progressively?), and in what duration.

Electrical work is potentially more difficult to schedule in more detail because of how these systems are designed. Conduit routing is not typically shown on plans, and routing is decided by electricians in the field. Electrical contractors argue that it is costly to model conduit routing. On this project, the mechanical contractor modelled the trapezes for the electrical contractor, indicating that the project's electrical contractor may not have had any capability to model conduit. This resulted in two rounds of follow-up questions via meetings in the succeeding weeks to understand what type of zone configuration was suitable for their work. Overall, their desired workflow was to work out from the electrical room, and fully complete each quadrant in one pass.

After meeting with each trade partner, the researcher and his adviser produced a current state of the Takt time plan for the Reverse Phase Schedule meeting. Figure 5-4 shows the floor divided into six zones, with a two-day Takt time per zone. The division of this floor was proposed using a set-based approach to feedback from the team, and how they preferred to work. The six zones were a result of the researcher trying to visualize how all of the trades could feasibly work in the space. The shaft work and electrical room were in the middle of the building, so it appeared to make more sense to have a middle set of zones, as opposed to a zone configuration that split the floor into quadrants, halves, or eighths. A middle set would allow trade partners to start work there, focus their effort on a smaller area (i.e., working out of the shaft or electrical room), then release the area to others, as opposed to claiming a larger space they may not have needed. The scope of the Reverse Phase Schedule meeting was to first review the workflows and information each team member shared (i.e., the current state), then schedule the overhead MEP rough-in phase of work per the zones created from the data collected in the individual trade partner meetings.

Figure 5-5 depicts how the different trades preferred to move around the space. The fire sprinkler contractor wanted to complete full lines of fire sprinklers. The sheet metal foreman wanted to work clockwise out from the shaft. The piping foreman wanted to work counter clockwise back to the shaft. The electrical superintendent wanted to work out from the electrical room and around the floor in a four-step sequence. The drywaller needed to frame the shafts, and then move out of the space. The workflows combined with the installation durations resulted in the first iteration of six zones, which the general contractor would control to, and each team member agreed to plan work through during the Reverse Phase Schedule meeting.

Figure 5-4 – Zones for overhead MEP rough-in phase

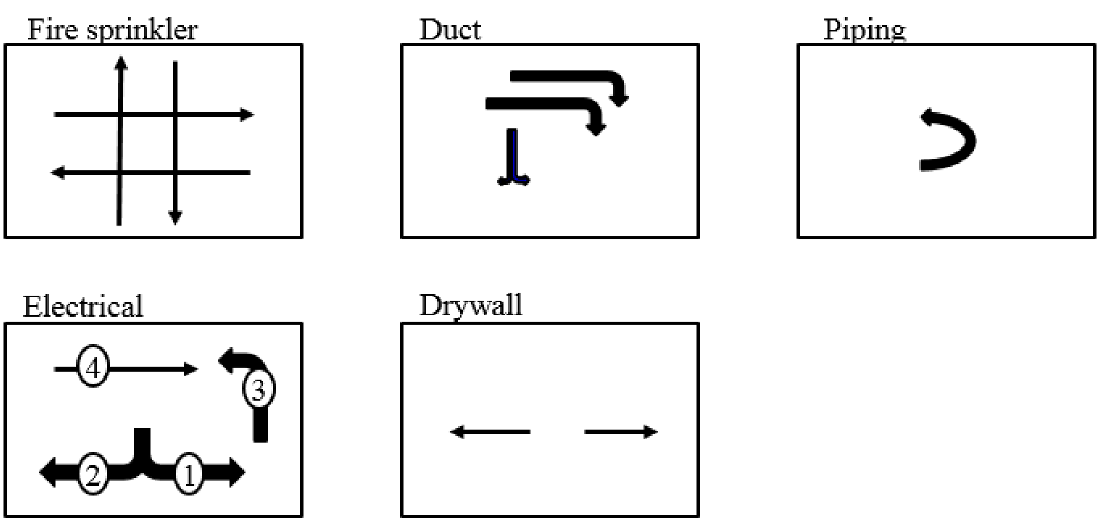


Figure 5-5 – Work flow direction for the five trades

When everyone was planning their work to this zone and Takt time configuration in the reverse phase scheduling meeting, the researcher (and scheduler for the project) observed that the trades did not plan to move through each area on a two-day Takt time, but rather to flow through each area, or just some areas, using different Takt times. The two-day Takt time paced the work and helped to manage the space by allowing trade partners to claim zones (work areas) where no other trade partner would be allowed without their permission for fixed amounts of time. Planning to zones and a Takt time allowed the different trades to communicate to everyone the zones they wanted to work in first, and what they could accomplish in the time period. Overall, the Reverse Phase Schedule meeting went well because the zones and Takt time required detailed planning from everyone; thus, everyone came to the meeting well prepared.

Two optimizing meetings in the weeks following the initial reverse phase scheduling overhead meeting focused on validating and improving the schedule. In each meeting, the researcher presented workflows to the team members showing the overall Line of balance schedule for the phase, and their individual flows of work (in order to demonstrate that the plan followed their preferred sequence and the work was continuous for each trade) (Figure 5-6). Line of balance techniques using Vico Control (2009) software helped to visualize the flows of work and identify areas to improve the schedule.

The initial overhead MEP rough-in schedule, based on the Reverse Phase Schedule Meeting, required 44 days to complete. The team identified opportunities to improve the total duration of the phase during construction, and make zone 6 a workable backlog area for the electricians. These opportunities may have not been seen, because it is difficult to understand what space is available, and the benefits of resequencing the work until the work is input into a scheduling engine (that rapidly calculates the activity starts/finishes and total duration of the phase).

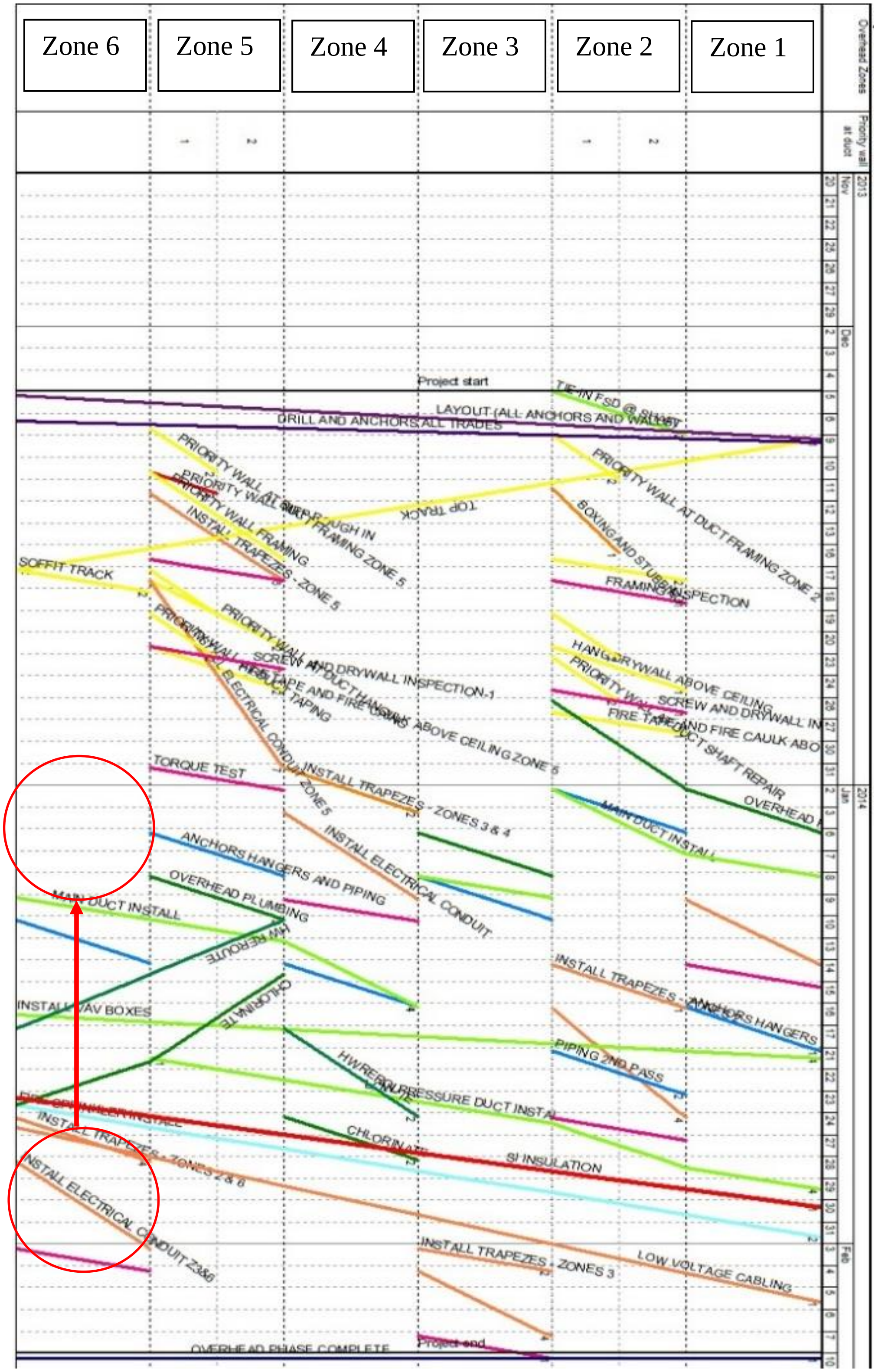


Figure 5-6 – Line of balance schedule for Overhead MEP Rough-in phase (circled area identifies the electrical work that could potentially complete earlier, as workable backlog)

5.4 TAKT TIME DEVELOPMENT FOR INWALL MEP ROUGH-IN PHASE

The inwall MEP rough installation phase focused on balancing the work between the plumber, electrician, and drywall trade partners. The researcher collected data from the plumber and electrician. The plumber had 46 man-days of work; the electrician had 112 man-days of work. The researcher asked the electrician to create their desired zones due to the large quantity of work they needed to perform in this phase. The rationale behind this decision was that if they had the most work, they were going to move the slowest through the space. Since the team can move only as fast as the slowest trade, setting up zones that improve the slowest trade's production rate will help the project overall (assuming the zone configuration is feasible for the rest of the sequence). By carefully studying their work, the electrician identified seven zones they could work through in a four-day Takt time (Figure 5-7). Overlaying the plumbing work (Figure 5-8) shows that the zones do not perfectly match a four-day Takt time, but they can be combined to work. For example, for the plumbing work, combining zones A and B fit into three Takt times, zones C and D fit into two Takt times, and E, F, and G would fit into one Takt time. The result was that the work could be scheduled with a delay such that the plumber could start two Takt times (eight days) behind the electrician and finish one Takt time behind.

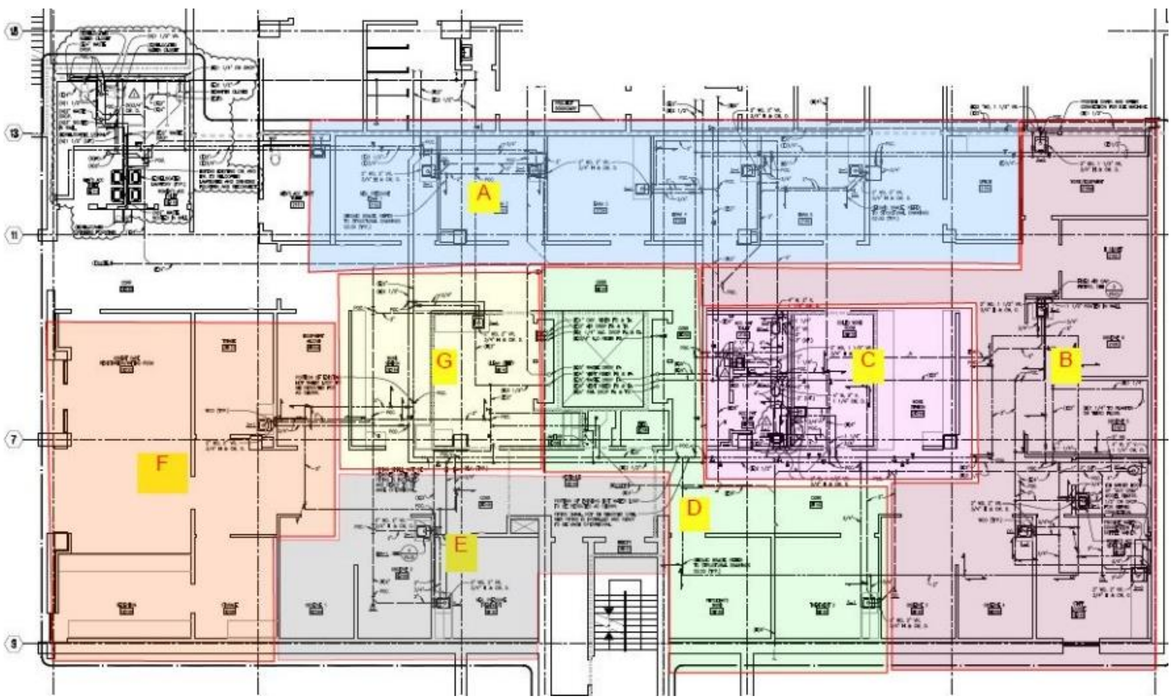


Figure 5-7 – Inwall rough installation zones requested by electrician

Figure 5-8 – Plumbing inwall rough installation work

The drywall trade partner was reluctant to commit to any zones because he was unsure of the sequence. In addition, he asked to install all the walls first, before any MEP rough installation began. The rationale was that they were going to prefabricate walls at their shop up to nine feet high, and could install everything rapidly if they had the space to themselves. Later, they would tie-in the framing to the ceilings manually with a second pass. Initially the second pass work was sequenced to be performed as "workable backlog" in the Master Schedule. In the Reverse Phase Schedule meeting, the drywall trade partner asked to perform the work in the inwall MEP installation sequence, and the team agreed. The change created a revision of the initial four-day Takt time plan. The zones remained the same, but the new sequence split the electrician's work (i.e., Step 4 work balancing) into two passes. The researcher created a Line of balance schedule to understand the new flow of work between the trades after framing was completed (Figure 5-9). This became the finalized production schedule (Step 5).

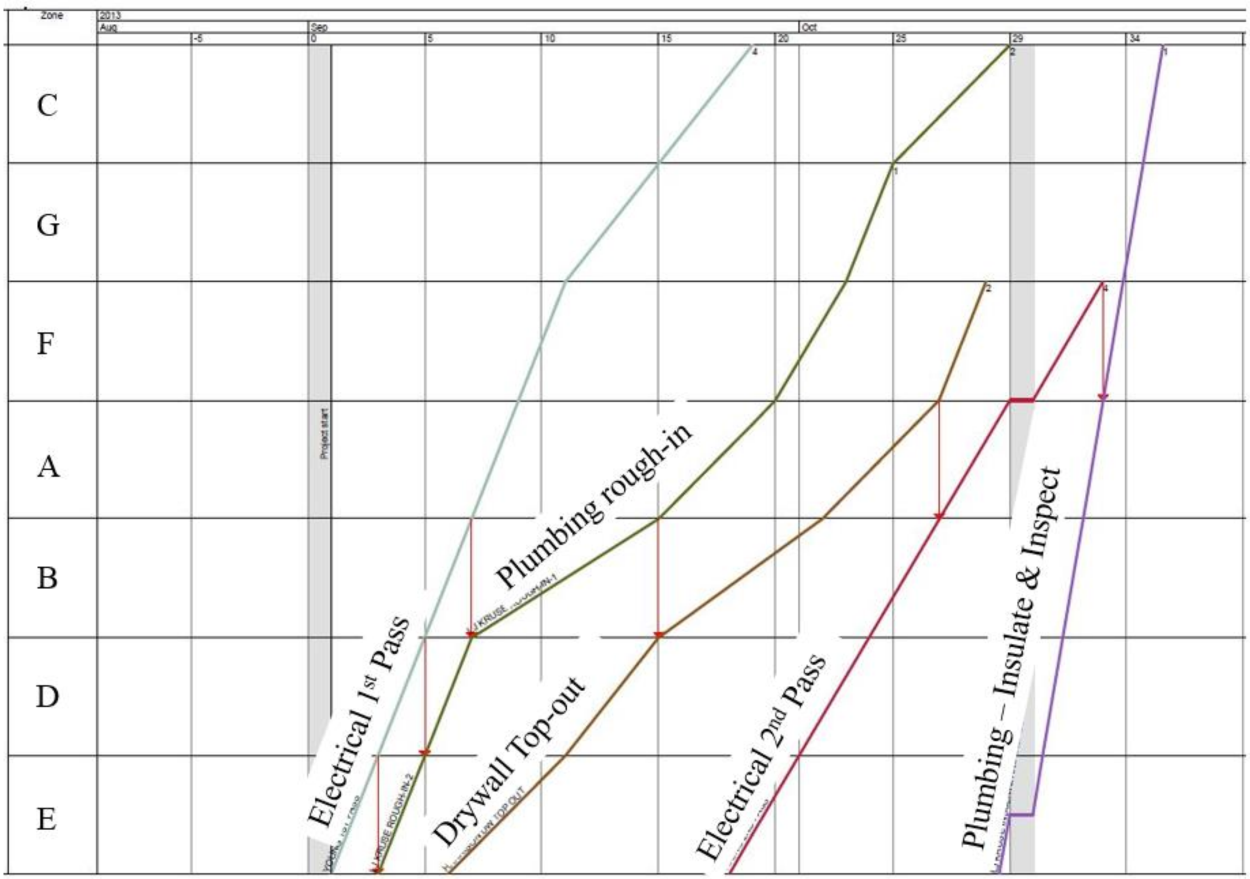


Figure 5-9 – Line of balance schedule using Vico Software with two electrical passes to accommodate the drywall Top-out

5.5 TAKT TIME DEVELOPMENT FOR FINISHES PHASE

The team planned activities for the finishes work through a single zone in a third Reverse Phase Schedule meeting with the project manager (general contractor), superintendent (general contractor), trade partners, and owner. Thus, the team skipped information gathering and defining zones in the Takt time planning method, and began by identifying a trade sequence. This was likely because the subcontractors responsible for the work were not bought out at the time of the Reverse Phase Schedule meeting.

After the Reverse Phase Schedule meeting, the superintendent proposed splitting the floor in half because the finishes activities moved faster than the MEP rough-in phases and required larger zones. With the given batch size, the superintendent identified work that did not need to be included in the Takt time plan because it did not require that the space would be occupied by a single trade. This work was moved "off-Takt" and included the following activities: starting up variable air volume (VAV) units, pre-testing fire smoke dampeners (FSD), chlorinating the plumbing, tie-in to fire alarms, furniture hook-up, installing thermostats, IT room wiring, and air balancing. The superintendent also said that flooring work could progress at night; thus, the work could move through the space however was needed.

While the team had a plan for the finishes, it was ultimately abandoned in the weeks before execution because it was not trusted. The lack of trusted occurred because the trades were not engaged in the planning. While the Takt time plan had zones, sequences, and activity durations, it did not have input from individuals performing the work who would validate that the plan was feasible.

5.6 RESULTS

5.6.1 OVERHEAD MEP ROUGH-IN PHASE RESULTS

The team modelled the building based on laser scan data of the existing space. The plan was to spend one week between demolition and the start of the overhead MEP rough-in phase to scan the space again, identify clashes in the model, and resolve any clashes immediately. However, the laser scanning company was not able to perform the scan and deliver the data back to the team in a timely manner, so the team proceeded with laying out on the floor based off bench marks set by the superintendent and snapped chalk lines for walls from the framer.

The average PPC for the overhead MEP rough-in phase, the first production phase for all trades, was 95% (Figure 5-10). The PPC calculation includes all activities in the weekly work plan; activities were also considered a miss if they completed early. The team members were able to work faster than planned through the areas with less labor, and they completed the work in 32 days (down from 44 days). The team used a visual control system to control the project on site, developed by the researcher specifically for the project. Appendix 1 gives details on the explanation and development of the visual planning system, as well as the reporting system used to collect manpower data.

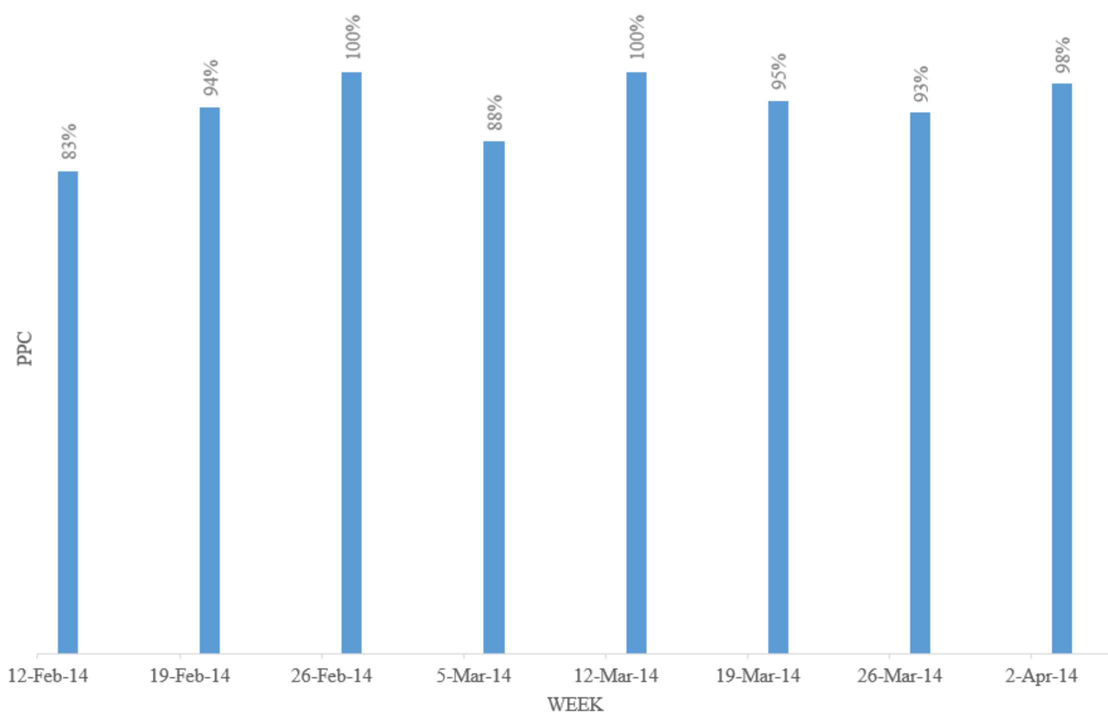


Figure 5-10 – PPC for Overhead MEP Rough-in phase

Feedback from foremen of different companies on the alternative method to planning was positive. The mechanical piping and HVAC trade partner project engineer commented, “Nine times out of ten, schedule acceleration costs us money. On this project, we went much faster than the initial schedule and it did not cost us a dime.” The electrical superintendent commented that the zones provided a great way of identifying where their own crews should be working. She knew that if one of her craftspeople was working in a zone not on the plan, she could immediately take action. She also commented that the floor was only 7,000 ft^2, so she still preferred larger zones than the six zones in the overhead MEP rough-in phase.

The team was particularly driven to work faster than planned, because 13 days were lost in the schedule in the previous phase for structural and demolition work. In the overhead MEP rough-in phase, the team recovered almost all of the 13 days by restructuring the work (circled in Figure 5-11). The circled activities that started earlier were all of the fire sprinkler tasks; install duct in zones 3 and 5; and install electrical overhead work in zones 1, 4, and 6. Due to the restructuring, the figure shows the initial contract schedule and the data from the “Pankow” schedule (the project master schedule, which captured the restructure). Figure 5-11 also shows how the team executed to the plan: compared to the Pankow schedule, activities started on average 0.68 days after the planned start, with a standard deviation of 2.68 days. Buffers in the individual durations may have existed because the trade partners did not completely trust the initial conception of the production plan. Nevertheless, when the trade partners realized they were going to be assigned zones to work by themselves, crew sizes and activity durations decreased.

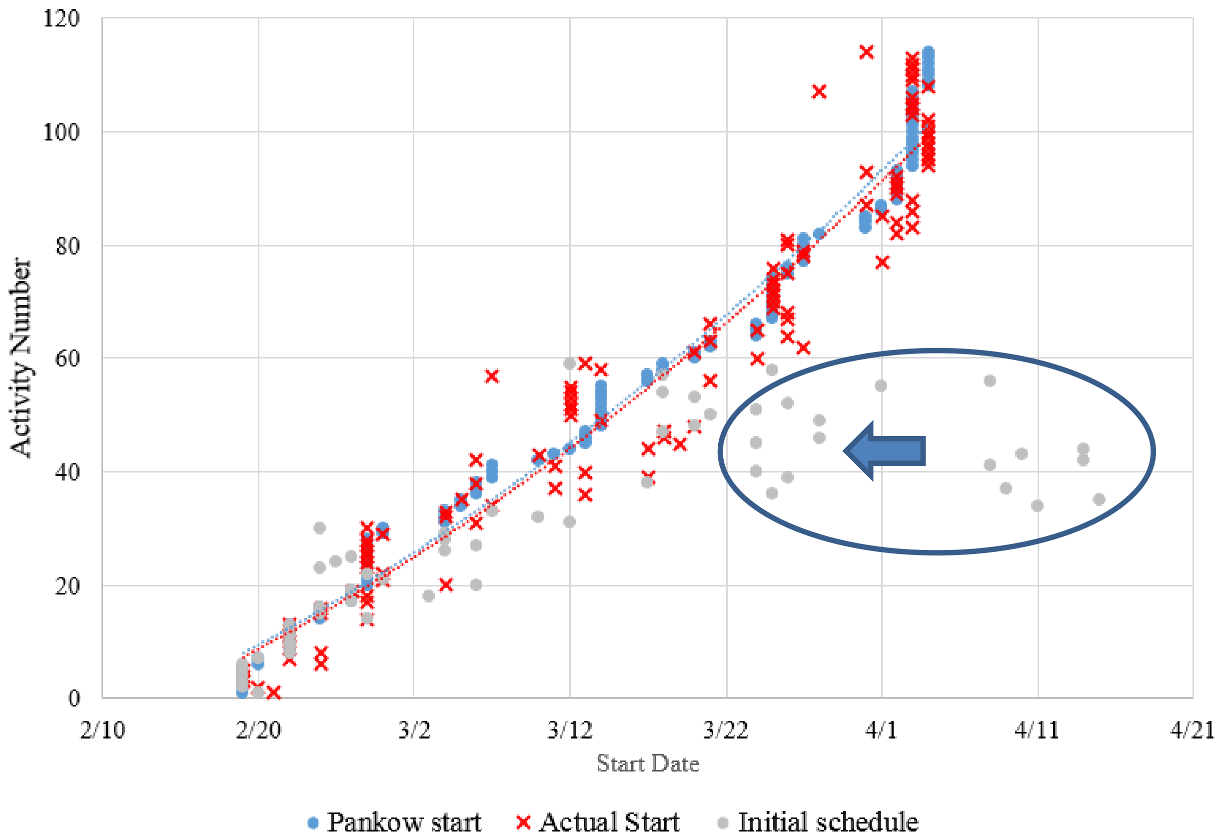


Figure 5-11 – Activity start times for overhead MEP rough-in (circled activities replanned and moved forward, saving time in the phase)

5.6.2 INWALL MEP ROUGH-IN PHASE RESULTS

The contract schedule duration (obtained from the Reverse Phase Schedule meeting) for the inwall MEP rough-in phase was 37 days. This schedule was reduced to 29 days by restructuring the work, but still kept the four-day Takt time. Figure 5-12 is a picture of the restructuring work the plumbing and electrical foremen completed to improve the schedule. By understanding the Line of balance schedule for the phase, the two foremen sat down with the researcher and edited the current schedule with a pencil on an 11"x17" sheet of paper to reflect how two crews from each trade could work through the space in a different sequence to improve the schedule. The team executed to the new plan, finished the work in 29 days, with an average PPC of 85% (Figure 5-13).

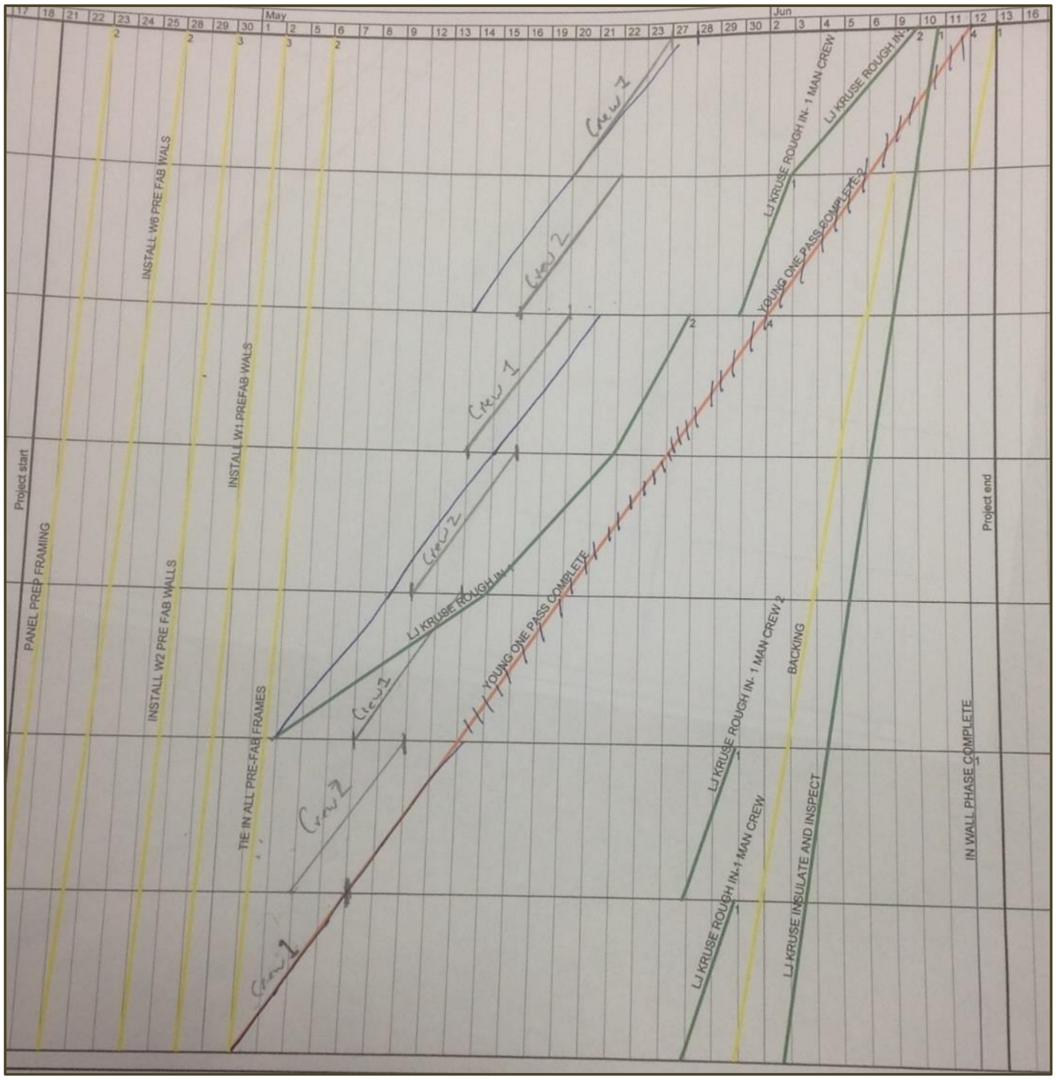


Figure 5-12 – Continuous improvement of inwall MEP rough-in schedule with mark-ups from the plumbing and electrical foremen

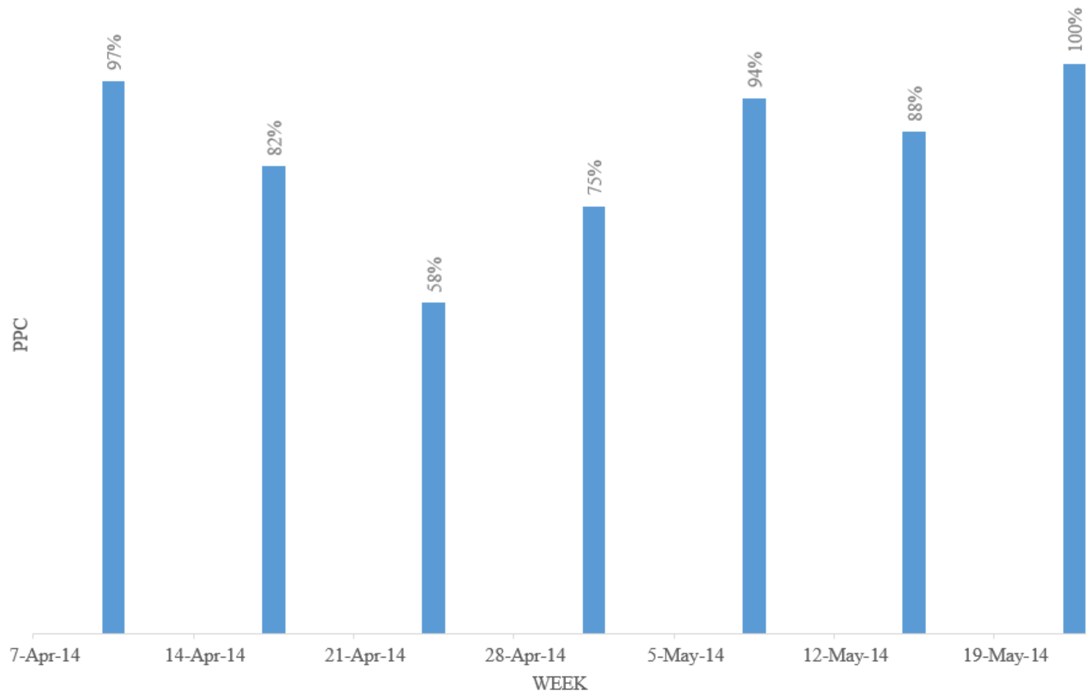


Figure 5-13 – PPC for Inwall MEP Rough-in Phase

Figure 5-14 categorizes the reasons the team missed activities for the overhead and inwall MEP rough-in phases. Though the team improved on the schedule, the primary reason why the team missed activities was an incorrect time estimate. Only a single activity (inwall plumbing rough-in) was missed due to unavailable material.

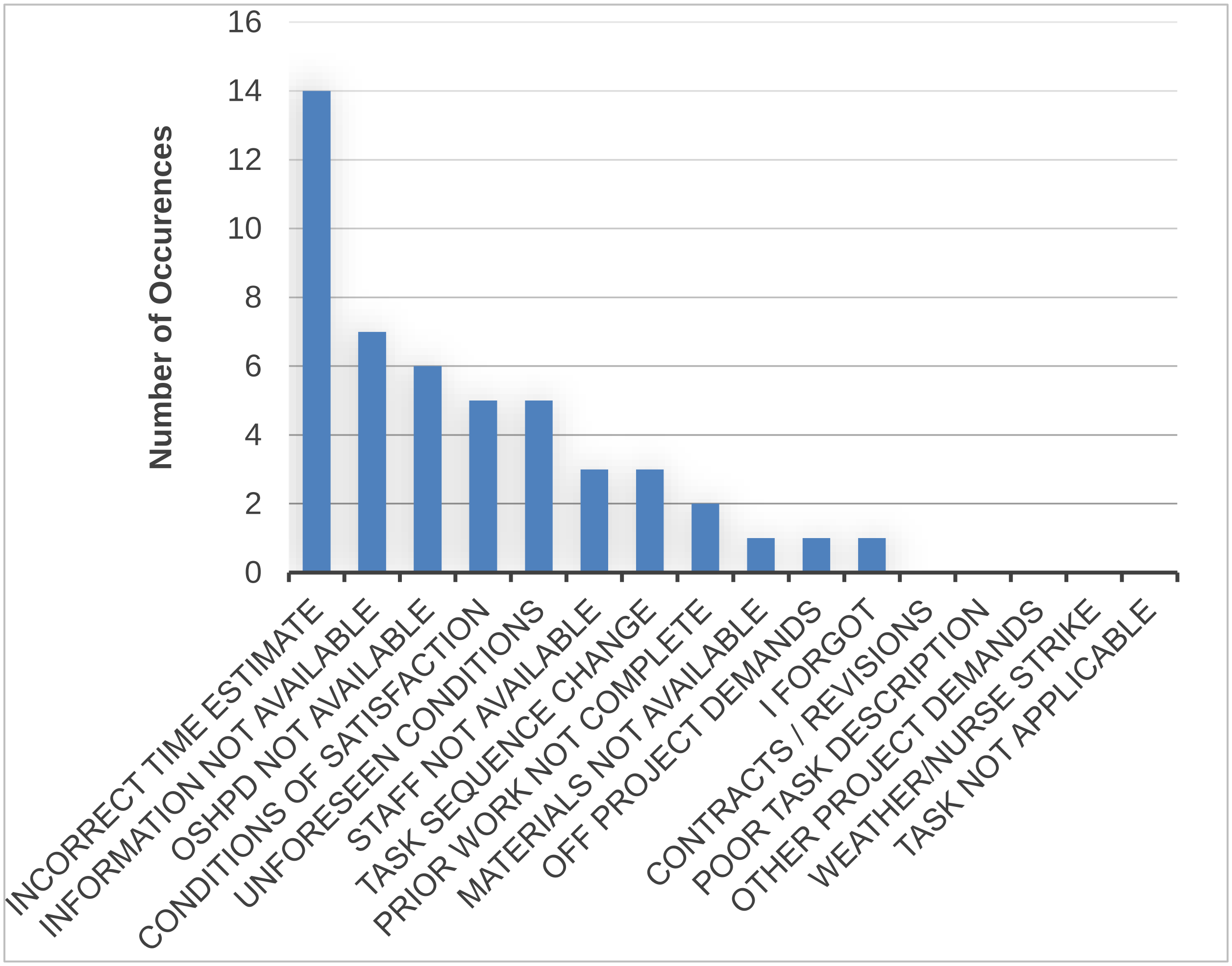


Figure 5-14 – Reasons Activities were Missed

Figure 5-15 reflects the planned versus actual starts. Since the restructuring occurred before the start of the phase, the "planned" reflects the new planned schedule. The average activity started 0.85 days after the planned start, with a standard deviation of 3.45 days. Two activities that contributed the most to the variance were insulation and testing activities, each of which were delayed by 15 days, but did not affect the handoff to the succeeding trade. If all of insulate and inspect activities are ignored, then the average start for each activity is 0.09 days after the planned start with a standard deviation of 1.29 days (i.e., the plan was followed).

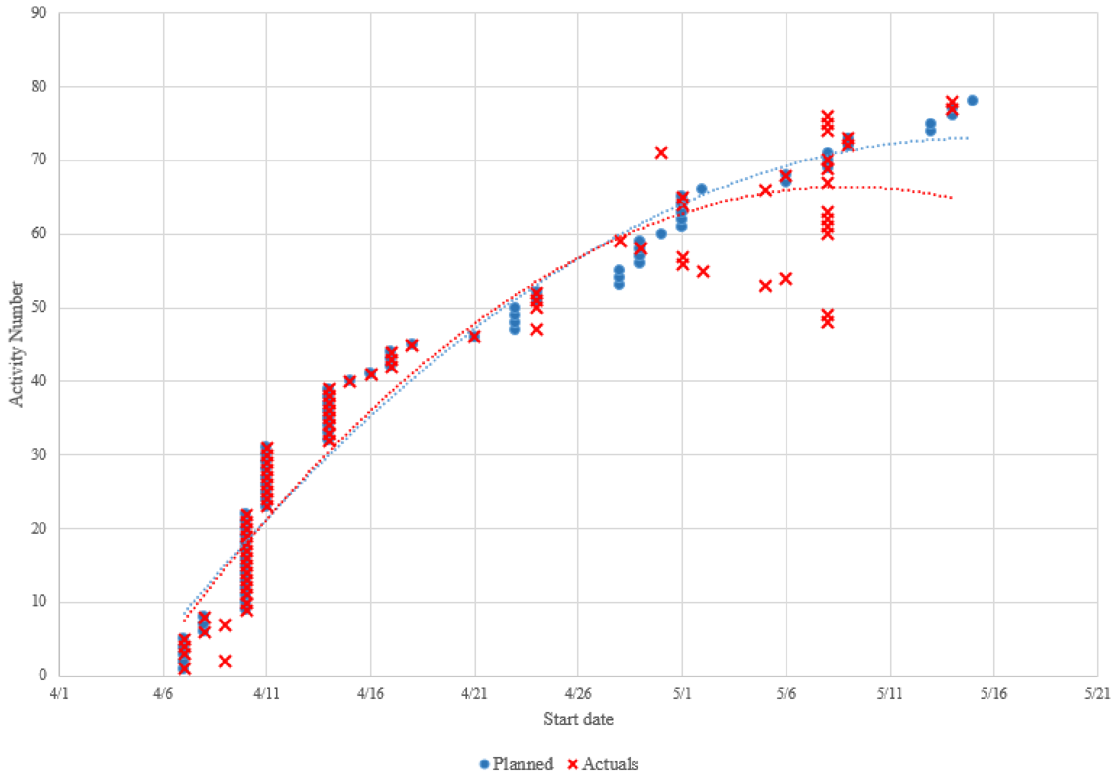


Figure 5-15 – Planned versus Actual starts during inwall MEP rough-in phase

5.6.3 EFFECTS ON MANPOWER

Figure 5-16 through Figure 5-19 graph the planned versus actual manpower charts for the electrical, duct, piping, and plumbing work during the overhead and inwall MEP rough-in phases. As shown in the graphs, all four trades required less manpower than stated in the scheduling data from the Reverse Phase Schedule meetings. The researcher obtained the daily manpower data from the foremen via a daily report collected by the project engineer. Figure 5-20 is an example of the daily report, which asked questions concerning manpower and crew location data. See Appendix 1 for further detail on the reporting system. The researcher compared the reported manpower with the most recently planned manpower. For the overhead MEP rough-in phase, the data came from the initial schedule developed from the Reverse Phase Schedule meeting. For the inwall MEP rough-in phase, the manpower data came from the schedule that reflected the update from the foreman to use two crews.

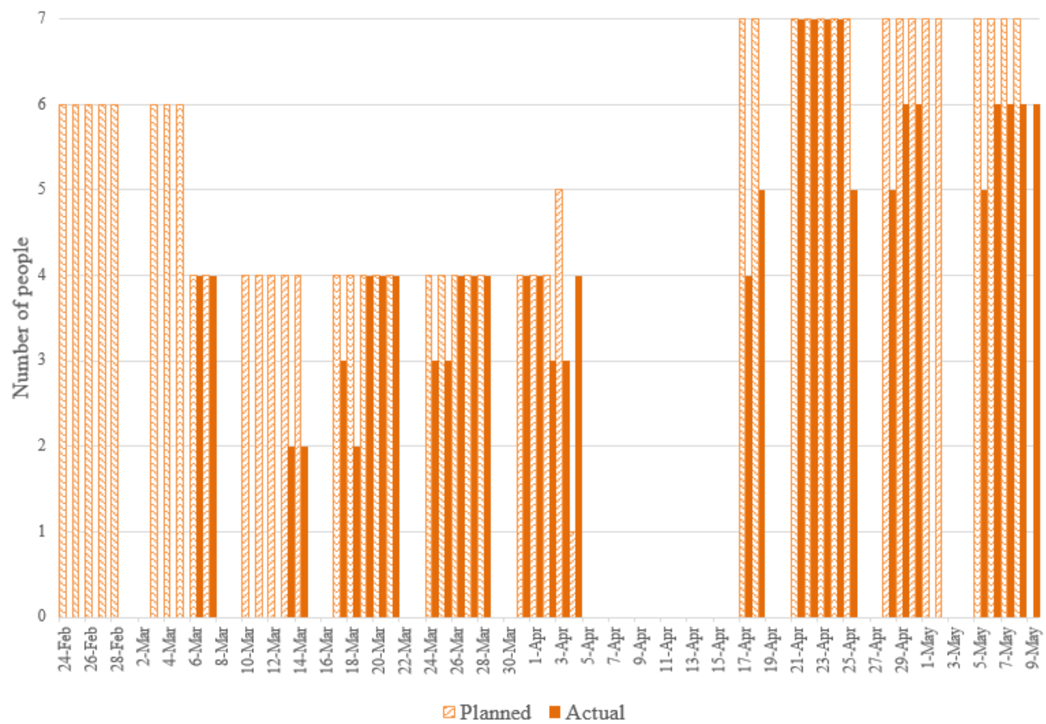


Figure 5-16 – Planned versus actual electrician manpower for all MEP installation

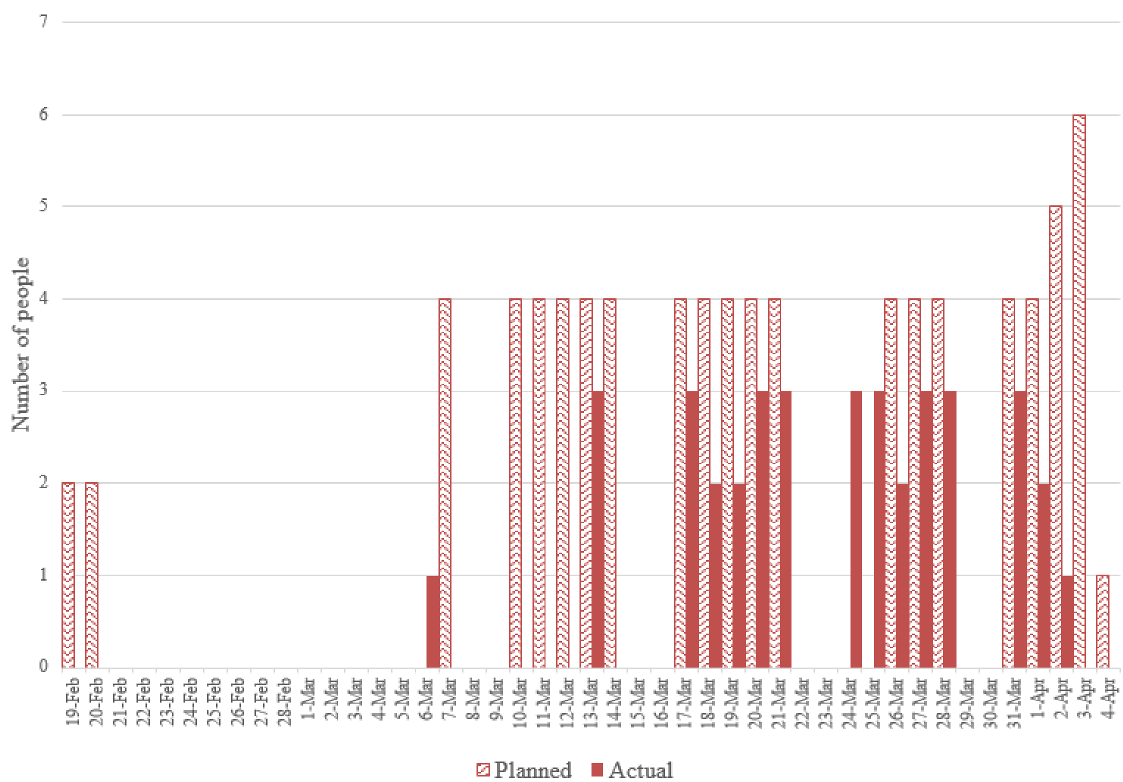


Figure 5-17 – Planned versus actual manpower for ductwork during MEP installation

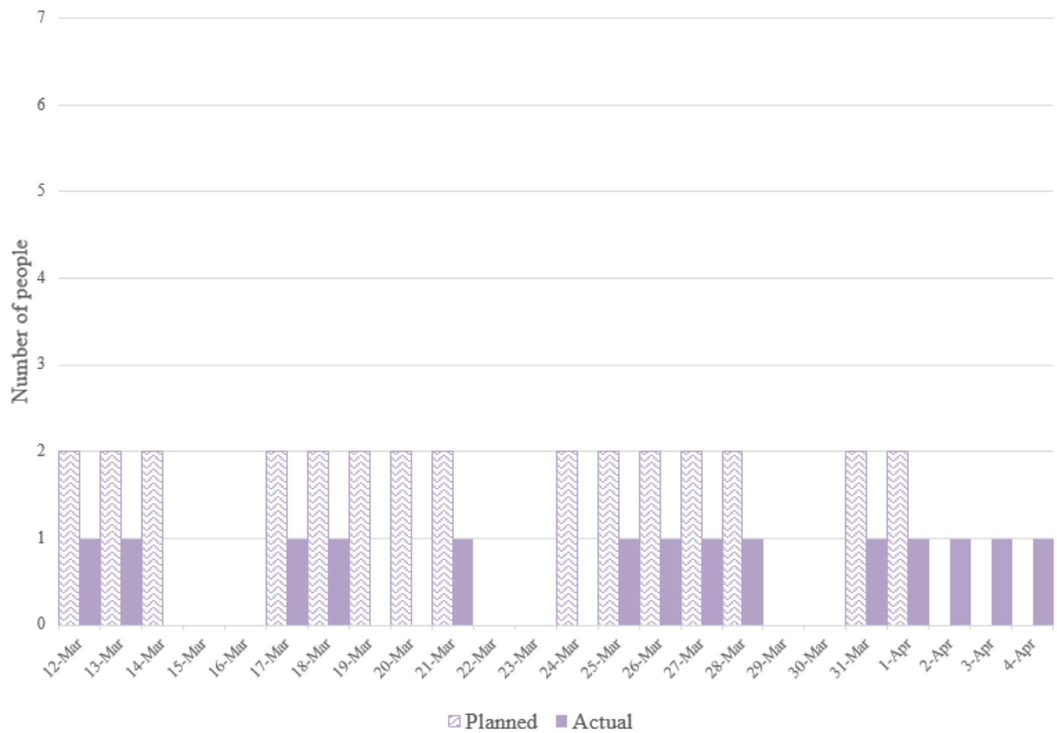


Figure 5-18 – Planned versus actual manpower for piping work during MEP installation

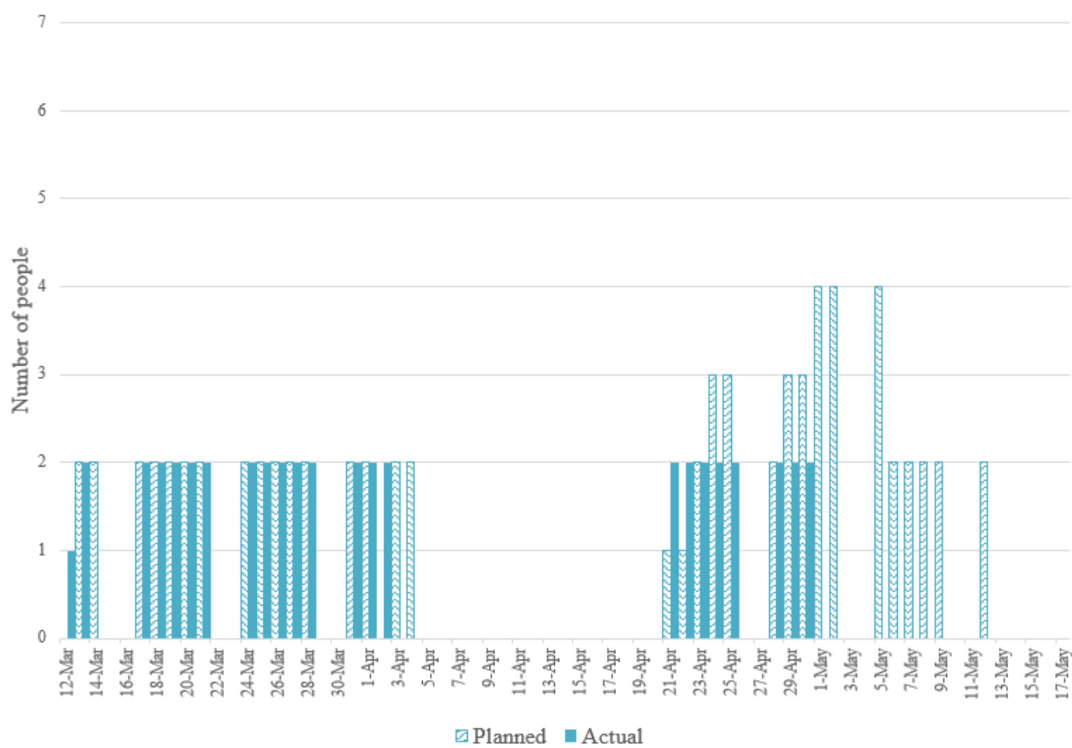
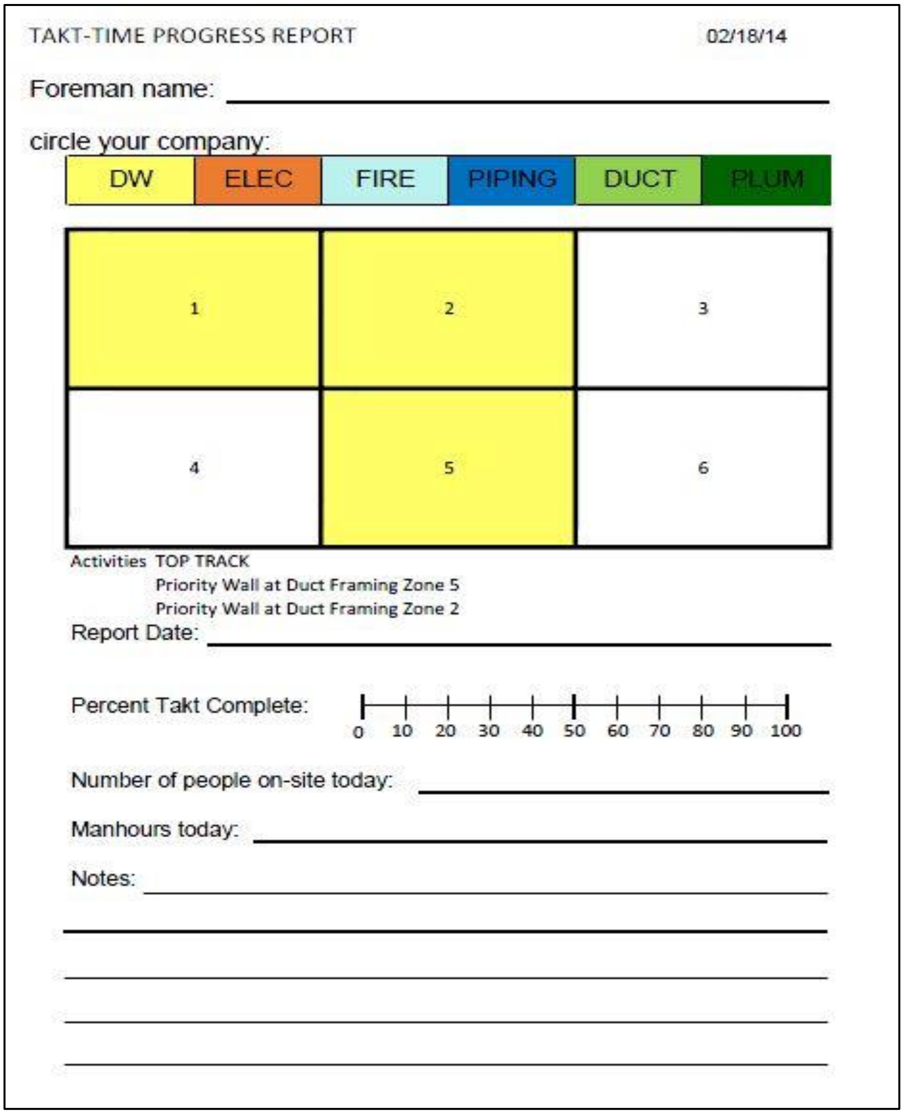


Figure 5-19 – Planned versus actual for all plumbing work during MEP installation


TAKT-TIME PROGRESS REPORT 02/18/14

Foreman name: ______

circle your company:

DW	ELEC	FIRE	PIPING	DUCT	PLUM

1	2	3
4	5	6

Activities TOP TRACK
Priority Wall at Duct Framing Zone 5
Priority Wall at Duct Framing Zone 2

Report Date: ______

Percent Takt Complete: 0 10 20 30 40 50 60 70 80 90 100

Number of people on-site today: ______

Manhours today: ______

Notes: ______

Figure 5-20 – Example of daily report

5.7 DISCUSSION

5.7.1 KNOW THE ACTIVITY SEQUENCE

Understanding the construction activity sequence (sequence of trades) before any Takt time plan is presented is critical, because if the sequence is not well understood, there will be additional iteration (i.e., another meeting) in the development of the Takt time plan. The sequence of the trades and implications on the Takt time plan may not be understood until the Reverse Phase Schedule meeting, so it is important to share incomplete information often with the team to avoid confusion or lead team members going astray on "what the plan is."

5.7.2 Reflection on Early Meetings

There were two types of questions discussed in the Takt time planning meetings prior to the Reverse Phase Schedule meetings: production and constructability questions. Production questions in this circumstance directly affect the Takt time. Example questions are, "Can you mark with a highlighter where your work is and write the duration/crew size by the mark?" and "How would you divide the floor up into six equal spaces of work, and what would this duration be?" Constructability questions in this circumstance relate to how the work is performed. Example questions are, "Can the fire sprinkler go in before ceiling grid, or is it more effective to drop the head after?" or "What work are you performing that requires a scissor lift?"

There is certainly a relationship between the two types of questions, and it is important to ask both types to identify feasible Takt times and zones. Some team members were able to identify on the floor plans where their work was, and what their desired durations and crew sizes were, while others focused on constructability and how they perform the work in a general sense. While helpful, the latter set of information does not immediately help to identify potential Takt times for the project phase. Thus, it was crucial to make sure that by the end of every meeting, the team clearly understood from every team member the amount of work everyone had on the floor and the distribution of work (i.e., the work density).

Early conversations provide an opportunity to address workflow and sequence concerns on the project. The superintendent for the general contractor made the remark that they rarely have these conversations for such small projects, but saw the importance of understanding the different trades' work. The Takt time conversations with the trade partners also revealed more of the assumptions in the original Master Schedule that was initially planned between the general contractor project manager and a superintendent who did not work on the project. The researcher hypothesizes that this schedule was created for proposal purposes to the owner, and the creators knew it would be revised later. The early meetings created several instances when team members revealed how they could perform work in alternative ways that would benefit the team as a whole (e.g., as noted previously, the fire sprinkler partner could install temporary sprinkler heads attached close to the main at the top of the ceiling and drop sprinkler heads after HVAC and piping were installed to let the HVAC and piping crews work quickly, with less chance of damaging live fire sprinklers). In short, Takt time planning provided the setting for detailed production conversations early so the project team could identify and apply the best production alternative.

5.7.3 CPM Schedules Versus Details of Takt Time Plan

The general contractor found that the number of activities in the CPM schedule increased significantly when details of the Reverse Phase Schedule with Takt times and zones were introduced into the Master Schedule. In addition, the logic, based on flows of work through space in a fixed time, became difficult to understand when looking at the overall schedule as a Gantt chart. The project manager commented that the CPM schedule had become tedious to update. As such, the general contractor adopted a "Takt book" that showed where each trade was working every day, to "see" the schedule more effectively for control purposes. For further iteration on each Reverse Phase Schedule, the information was also presented in a Line of balance schedule via Vico Control 2009 in order to quickly identify opportunities for improvement. In fact, the project team, including the owner, liked the effectiveness of the Line of balance schedule for optimization meetings so much that the final schedule became the one produced by Vico Control.

5.7.1 Use of Workable Backlog

Takt time planning enabled the framing trade partner to use workable backlog effectively in the inwall phase. The walls were prefabricated offsite, and were not a part of the inwall MEP rough-in phase. However, during the inwall MEP rough-in phase, the framing trade partner had to install prefabricated soffit drops and manually frame some sections of the walls that went full height. An agreement was made that the framing foreman had the freedom to plan this flexible work around the MEP trade partners. Because of the daily color-up detailing where plumbing and electrical work would be performed, he knew which areas were available and successfully worked around the other trade partners. This was an example of how the clearly communicated Takt time plan enabled the execution of workable backlog in a decentralized manner, without ever becoming critical to the project.

5.7.2 Subcontracted Work Versus Trade Partner Work

The researcher observed a difference between how the work was scheduled to Takt times between work bought out and subcontracted by the general contractor, and work performed by different trade partners. When trade partners had a specific sequence or constraint to their work (e.g., we have to install all exterior walls first, or we need to complete full runs of conduit; thus, we need this whole space), that constraint also affected the Takt time plan. There was more flexibility regarding how work would be performed and in what time frame with subcontracted work because the sequence could be dictated. However, a pitfall to dictating the sequence is that it may cost more than work performed in a different manner. This was an important lesson because it revealed that Takt time planning is feasible for integrated project delivery teams, and more experimentation was required to understand how to implement Takt time planning with subcontracted trades. Case study 3 is an example of Takt time planning with hard-bid trades.

5.7.3 Takt is Iterative

It is important to emphasize the iterative nature of Takt time planning. One issue team members raised was why there were no dates on the pull plan in the Reverse Phase Scheduling meeting. It would seem logical to include dates based on the Master Schedule to constrain the pull plan to a fixed duration. Thus, if the pull plan scheduled to a particular Takt time configuration did not meet the milestone constraints, activity durations would have to be reduced. However, this may not produce the best schedule the team can create. On this project, each phase was pull planned to different Takt time durations, then input into a P6 schedule, as well as Vico Control 2009 (and in later phases, just Vico Control 2009), then the plan was reviewed and improved with the team at a follow-up meeting. Before the follow-up meeting, the researcher used different activity crew sizes and duration assumptions in different alternatives to find additional schedules with shorter durations. In the follow-up meeting, team members also offered input on how to improve the schedule (e.g., the drywall contractor said they could tape the area faster than initially stated in a previous Reverse Phase Scheduling meeting).

A challenge from the team for the iterative nature of Takt time planning is that when Reverse Phase Schedules are created to specific zones and Takt times, the resulting schedules may be perceived as finalized, even though the team still needs to verify that the sequence and Takt time work through all of the zones. The result is that the team may be more resistant to change the zones or Takt times and 'plan the work again,' even if the changes would create a more balanced plan.

5.7.4 Boundary Limits of Takt Time Planning on Small Projects

The researcher helped a project team apply Takt time planning to a partial one floor retrofit of an occupied, operational hospital. A challenge for identifying balanced Takt times was that there were no floors or large areas of work to scale to (i.e., the plan just flowed through a 7,000 ft^2, rather than a five floor building). Manipulation of crew sizes is one primary method used to balance trade durations in zones. Smaller zones limit the range of crew sizes. Consequently, the minimum/maximum crew sizes and different work densities for each trade at each phase made a perfectly balanced schedule impossible. Regardless, Takt time planning did reveal that the team could work together and manage the space they had at a much higher resolution (i.e., at a higher level of detail in areas smaller than the whole space), as opposed to everyone working all over the floor at once and fighting for space. Thus, while the overhead MEP rough-in phase Takt time plan did not produce a perfectly balanced schedule for production, it did provide a schedule that accounted for space and allowed the team to work productively throughout the entire floor. In addition, the general contractor could then control the work to the schedules of production in an organized fashion.

5.7.5 Observations on the Lookahead Process

Mills had a team of foremen who worked well together. They collaborated in the field, and talked throughout the day about the work that they needed to complete. In interviews, all of them commented that the daily boards clearly designated who owned the space and helped guide the conversations (Figure 5-21). If need be, a few members of a crew would move into a zone and perform work out of the planned sequence for a short period for a single component that did not fit the schedule logic. The foremen would look ahead into the future work zones and clearly see small obstacles where a piece of duct or piping would have to go in before the planned sequence of activities. If this type of daily coordination is not performed or planned correctly, it will impact the downstream trades. This is essentially a 'screening' of activities in the Make Ready process in the Last Planner System. Thus, screening on this project was good for two reasons: the skill of the foremen and the clear communication of the schedule at a detailed level tied to zones via a visual schedule in the field.

Figure 5-21 – Example of field board showing daily plan; Appendix 1 provides more detail regarding what was shown and how these sheets were automatically generated

5.8 CASE STUDY CONCLUSION

The Mills case study of Takt time planning on a one-floor retrofit reflects findings and lessons learned about how a Takt time plan developed for three interior build out work phases. These initial meetings, for the Parade of Trades game and individual trade partner meetings for production and logistics questions, proved valuable for driving the conversation in the Reverse Phase Schedule meeting, and revealed new alternative sequences for the IPD team to perform the work. In the initial meetings with team members, it was crucial to ask questions that clearly identified the density of the work (i.e., where is the work located, what is the crew size, and how long will it take to perform?). Effectively communicating that the zones and Takt time for each phase are flexible was crucial at every step in the development of the Takt time plan in order to inform people about the plan and keep them engaged in the planning process.

The project used the Takt time plans for the overhead MEP and MEP inwall rough installation phases. The finish sequence had an initial Takt time plan, but it was abandoned when the team conducted a second Reverse Phase Schedule meeting with the subcontractors in the room and a facilitator who was not aware of the Takt time planning the team was doing. Each phase using Takt time finished faster than the contract schedule; the 44-day overhead MEP rough-in phase finished in 32 days, and the 37-day inwall MEP rough-in phase finished in 29 days. The cost of using Takt time planning was the time spent in the kick-off meeting, in individual trade contractor meetings, and by the project engineer posting and collecting the daily Takt time data. The project concluded with all trade partners making their contracted profit and an additional bonus shared by all parties on the project.

CHAPTER 6 CASE STUDY 2: PSYCHIATRIC EXPANSION PROJECT

6.1 INTRODUCTION

This chapter presents a case study of Takt time planning developed for interior MEP construction of a pre-cast psychiatric facility in Sacramento, California. The scope of work planned to a Takt time began with laying out mechanical/electrical/plumbing (MEP) components on the concrete floor, and ended with hanging gypsum wall board. The project met various building codes, including California's earthquake design codes and the code requirements from OSHPD. The project was a $16,000,000, two-story, 26-bed, 19,000 ft^2 (1,800 m^2) psychiatric care facility expansion to an existing 120-bed hospital. It was delivered with an Integrated Form of Agreement (IFOA) contract using shared risks and rewards.

Development of a Takt time plan for the interior MEP trade activities was selected by the project executive for the general contractor due to the speed of the construction schedule and the potential need for the interior MEP activities to work at the same pace. Construction of foundation work began in March 2015, and the entire project was planned to be ready for the owner to move in October 2015. The interior work was released by the pre-cast erection work in two phases consisting of separate halves of the building. The interior pre-cast walls contained rough installed ("rough-in") MEP components that in theory, enables shorter inwall MEP rough-in activity durations, because installation work is already completed upon pre-cast erection. This chapter covers the development and execution of the Takt time plan for this project.

6.2 CASE STUDY TIMELINE

Figure 6-1 presents the timeline of the case study. Construction started on 2/14, the week before research began. Due to the urgency to produce a plan for interiors, the kick off meeting for Takt time planning and the data collection occurred on the same day, with the data collection from the trade partners immediately following the kick off meeting. The owner was not present in the kick off or production meetings. The general contractor held production meetings with the trade partners (represented by their project managers and foremen), instead of the individual meetings used in case studies 1 and 3. The schedule was finalized in the second week of April, and the planned start for the Takt time work was 5/11. Delays in the pre-cast erection and cast-in-place concrete prevented the interiors team from starting in May, and the first Takt time activity started on 6/14. The project team divided the project into two phases of interior build out based on how batches of the pre-cast superstructure were released.

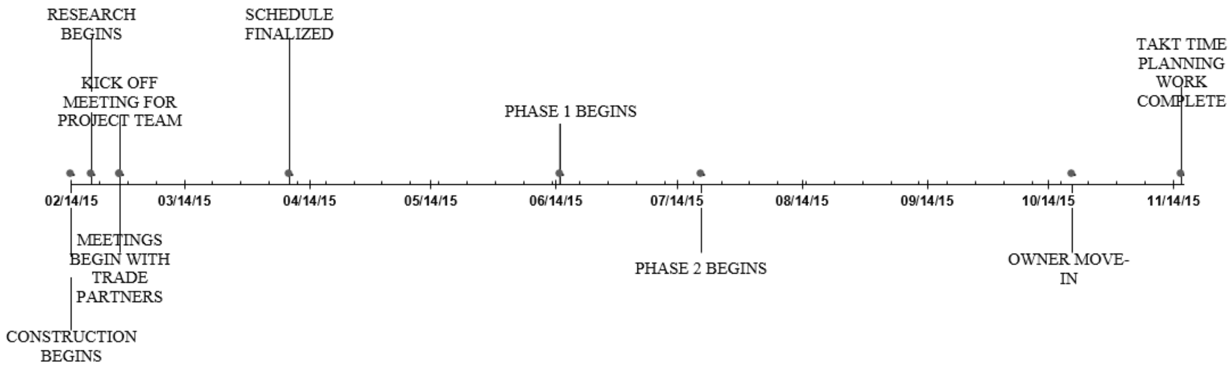


Figure 6-1 – Case Study 2 timeline

6.3 Development of Takt Time Plan

6.3.1 Initial Production Planning

Production planning started with milestone planning one month before site work began. The team identified Takt time planning as a means to deliver the fast schedule, and agreed to go through the Takt time planning process. The initial team was comprised of foremen for the plumbing, HVAC, and electrical scopes; project managers for the same scopes plus drywall; the general contractor represented by a superintendent and project manager; the architect; and the structural engineer. From here on, the production team refers to the foremen, project managers, superintendent, and researcher.

The researcher started with understanding the current state of the plan and project. Figure 6-2 presents the installation durations provided by the trades in an initial pull planning session held before the start of this research. The resulting schedule is not shown here, but what is evident from the figure is that these durations would create a schedule that would be significantly longer than the contracted end date if each trade were to have the space to themselves, and the work had finish-to-start relationships. Figure 6-3 shows a colored map of the production areas. Per the initial pull plan, the activity durations for each individual trade were not balanced through the initial zones (A, B, and C). The stated rationale for the three zones was that zone A contained the patient rooms (e.g., similar work), and zone C had a work density roughly equivalent to B for each MEP trade. Zones B and C contained the spaces necessary for staff and operations (exam, break area, nurse station, storage, etc.). Per the initial pull plan, the activity durations for each individual trade were not balanced through the initial zones.

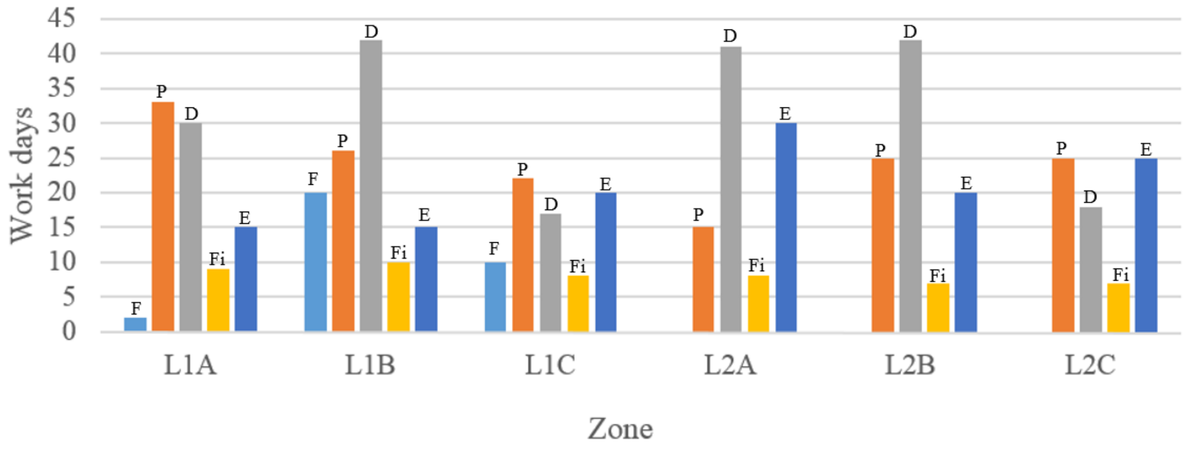


Figure 6-2 – Installation durations provided from initial pull plan meeting per zone (L1A = Level 1, Zone A; L2B = Level 2, Zone B, etc.) and per trade (F = Framing, P = Plumbing, D = Duct work, Fi = Fire sprinkler, E = Electrical work)

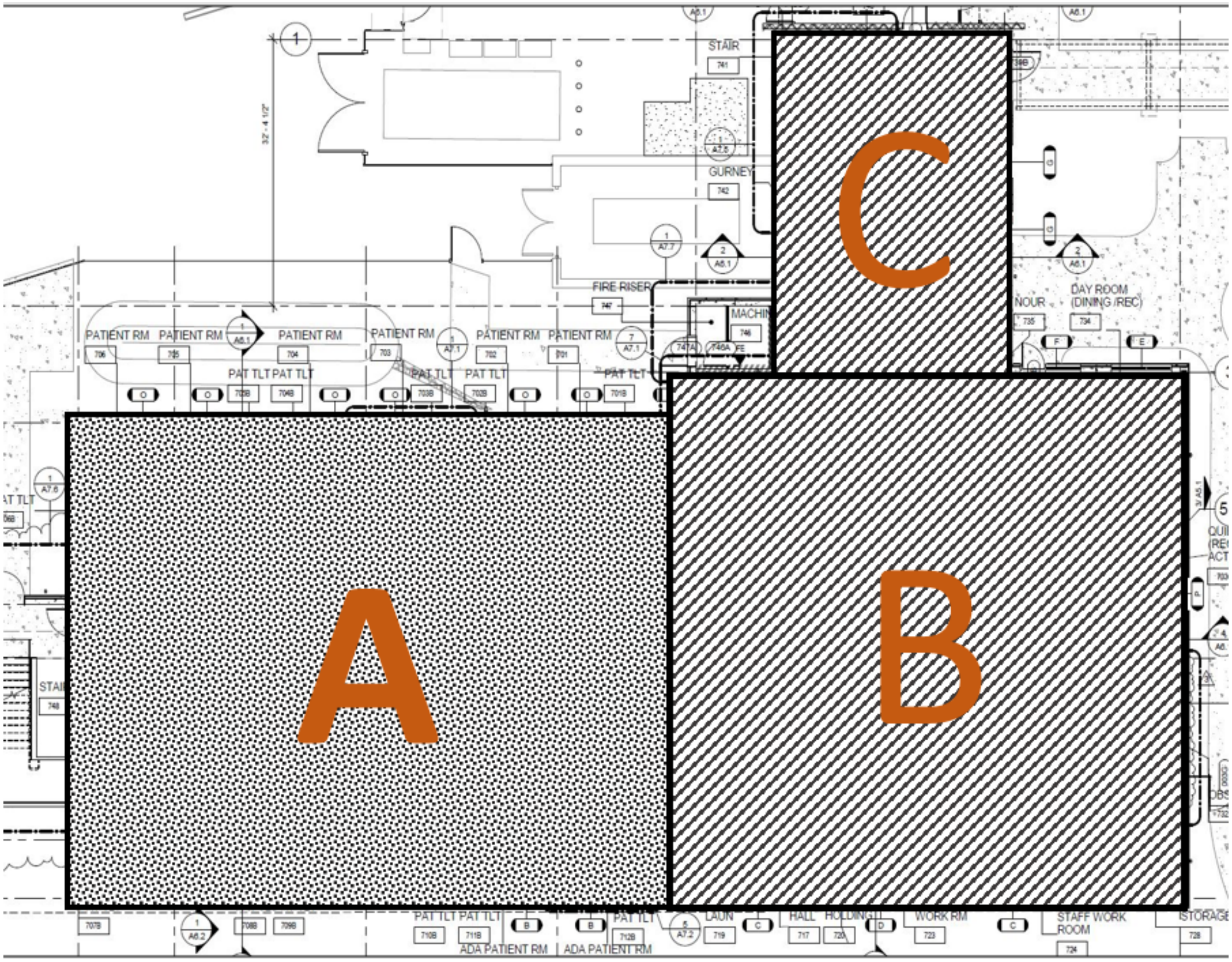


Figure 6-3 – Production areas for MEP installation phase

Early meetings with the production team aimed to plan the interior work, reset the major milestones in the project, and identify the demand rates for the different phases of work. Based on the milestones and concrete floors release dates to the interior trades, the researcher calculated the required minimum Takt time to complete the schedule in the allotted time by dividing the total number of days for a phase through one zone by the number of activities that needed to move in succession through the zone (e.g., 55 days for a zone with 11 activities results in a five-day minimum Takt time if all activities move at the same pace). In these early meetings, the team agreed to release the pre-cast concrete work in two batches to split the project into two phases. These phases would also become the zones through which the trade activities would work (e.g., Phase 1 = zones B & C, Phase 2 = zone A). The team then aligned their Takt time plan to four zones: Phase 1 and Phase 2 through the two floors of the project, Levels 1 and 2.

Figure 6-4 presents the different schedule scenarios created by the researcher on a Line of balance diagram, each represented as a single activity. The vertical lines reflect the start date for the finish phase and how much time would remain to complete that scope (also including testing and starting up the equipment). The rationale for the different scenarios was to communicate to the team how different Takt times provided different amounts of time for the remainder of the work. The researcher assumed each scenario contained 10 activities (five passes of MEP overhead, wall framing, and four inwall MEP passes) through two zones in Phase 1, 11 activities through two zones in Phase 2, and one week for layout/fire sprinkler work. With this information, the team decided on a Takt time, balanced the work, and created a schedule.

Based on the production data collected from the initial pull planning session, a 10-day Takt time was the proposed target. However, the scenario analysis showed that this Takt time would not meet the project requirements (e.g., the demand rate) based on the assumption of how many passes would be required through four zones. The option that came closest to meeting the constraint of leaving eight weeks for the finishes work was working to a five-day Takt time with one crew, through four zones, divided into two phases of work. This scenario became the target for the team. The project then had a design target for their production team to work to and structure the trade activities to meet this handoff.

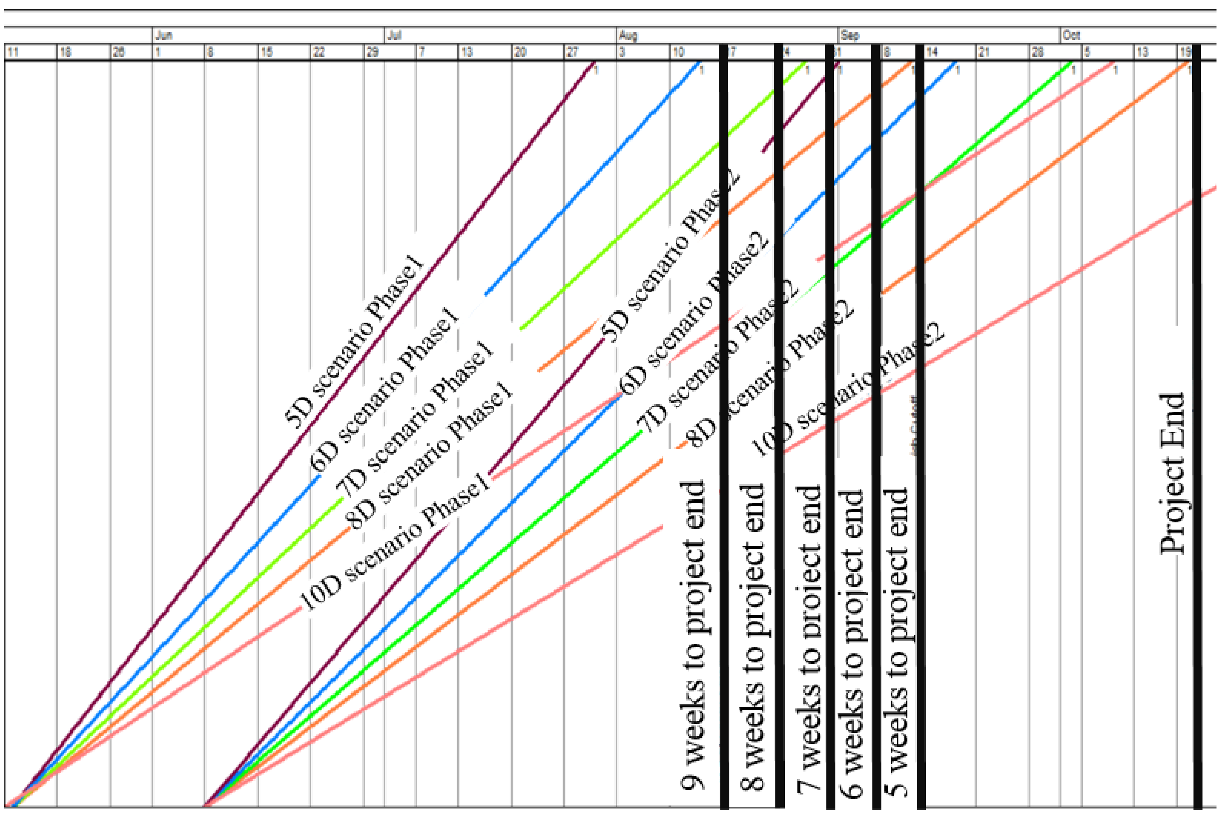


Figure 6-4 – Takt time scenario calculations; the five-day ("5D") scenario was selected by the team

After the production team agreed on the target, they began to validate the sequence identified in the pull plan and durations. The durations were validated by marking up the plans for the mechanical piping, duct, and plumbing work. For example, from this process the duct foreman identified that he had eight days of duct work per phase per floor. The electrician did not mark up floor plans, but the foreman committed to completing his work in whatever time the other trades were allowed. The electrical foreman was confident his crew could complete the work as fast as the other trades, because much of his work was in the pre-cast walls and it would arrive at the site complete. Electrical site work was limited to the electrical room, minimal overhead work (just one rack that would take one man three days to complete), and minimal inwall MEP rough-in the framed walls. During two meetings, the team committed to a 14-activity sequence at a five-day Takt time for the overhead and inwall MEP rough-in work shown in Figure 6-5, where each activity was formed by a collection of smaller tasks.

1 PRECAST ERECTION (TAN)	2 CAST IN PLACE CONCRETE (Lt. Grey)	3 DRILL AND LAYOUT ANCHORS, TOPTRACK (Grey)	4 CAST IRON/ FIRESPRINKLER / VERTICAL SHAFT WORK (Orange)	5 PRIORITY FRAMING / TOP DOWN (lt. Purple)	6 OH DUCT / PRE RACK PLUMBING (Blue)	7 OH DUCT / PRE RACK PLUMBING (Blue)
8 OH INTECH WET / ELECTRICAL HOMERUNS (Green)	9 TEST AND INSULATE (Yellow)	10 2ND PASS FRAMING (SOFFITS/WALLS/ HARD LIDS) (Red)	11 ELECTRICAL INWALL ROUGH and Branch (Lt. Blue)	12 PULL WIRE / PLUMBING ROUGH IN (Lt. Blue)	13 HANGING (Lt. Green)	14 TAPING (Purple)

Figure 6-5 – 14-activity sequence for the Interior MEP work (starting with pre-cast erection and ending with taping)

Only one of the 14 activities, OH DUCT/PRE RACK PLUMBING, required two five-day Takt times. The reasons for this were that the duct work was dense through zones B&C and could not fit into five days and, the plumber needed to install mechanical piping before the duct was installed in some areas in that zone. Furthermore, the amount of work the plumber needed to install before the duct sequence did not require the entire space for a Takt time, so the production team decided to combine the activity with a duct installation sequence. All trades were amenable to a five-day Takt time for the remaining activities, even if the sequence was not what they would have individually preferred. The researcher rationalizes that they were amenable because they were incentivized to improve the project as a whole. The electrical room work was set as a leave-out area due to the relative work density for a single trade from this Takt time plan. The electricians committed to performing this work around their Takt work. The 14 activities were also known as "train cars" on site, emphasizing that everyone needed to move through the space in the same order at the same rate.

Following the agreement on the 14-activity sequence, succeeding production planning meetings aimed to: (1) identify the specific handoffs of work for every activity; (2) identify the priority walls (i.e., walls that needed to be framed before overhead MEP equipment was installed); and (3) restructure the work as needed to keep a feasible production schedule.

It took one meeting to populate a list of handoffs for all the activities in this phase. The researcher populated the list by placing one poster-size sheet of paper on the wall for every sequence for every week (i.e., "OH DUCT/PRE-RACK PLUMBING had two sheets, one for each week). The trade partners simultaneously filled out the sheets and reviewed the work as a team at the end. The meeting revealed to the researcher how smaller activities could be sequenced within larger activities, and when work really needed to be done. For example, there were multiple alternatives for insulating mechanical piping and duct. The electrical work also had flexibility regarding when it could be performed, so the team decided to create an activity for electrical inwall rough-in, and planned the pull wire task to proceed at the same time as plumbing rough-in.

Figure 6-6 reflects the initial color-up of the priority walls in the first floor of work. The framer identified approximately 700 feet of priority walls on the first floor. Future production meetings needed to identify how installing these walls early impacted the flow of people and material during the overhead MEP work (e.g., are areas still accessible, what is the largest run of duct that can now fit through the space, how will material delivery be coordinated, etc.). In addition, because the priority wall activity contained about 80% of their total framing, the team examined how to restructure the work into other activity sequences during the production meeting. The team decided to move layout and MEP coordination activities into the 'Layout' and 'Vertical Work' activity sequences.

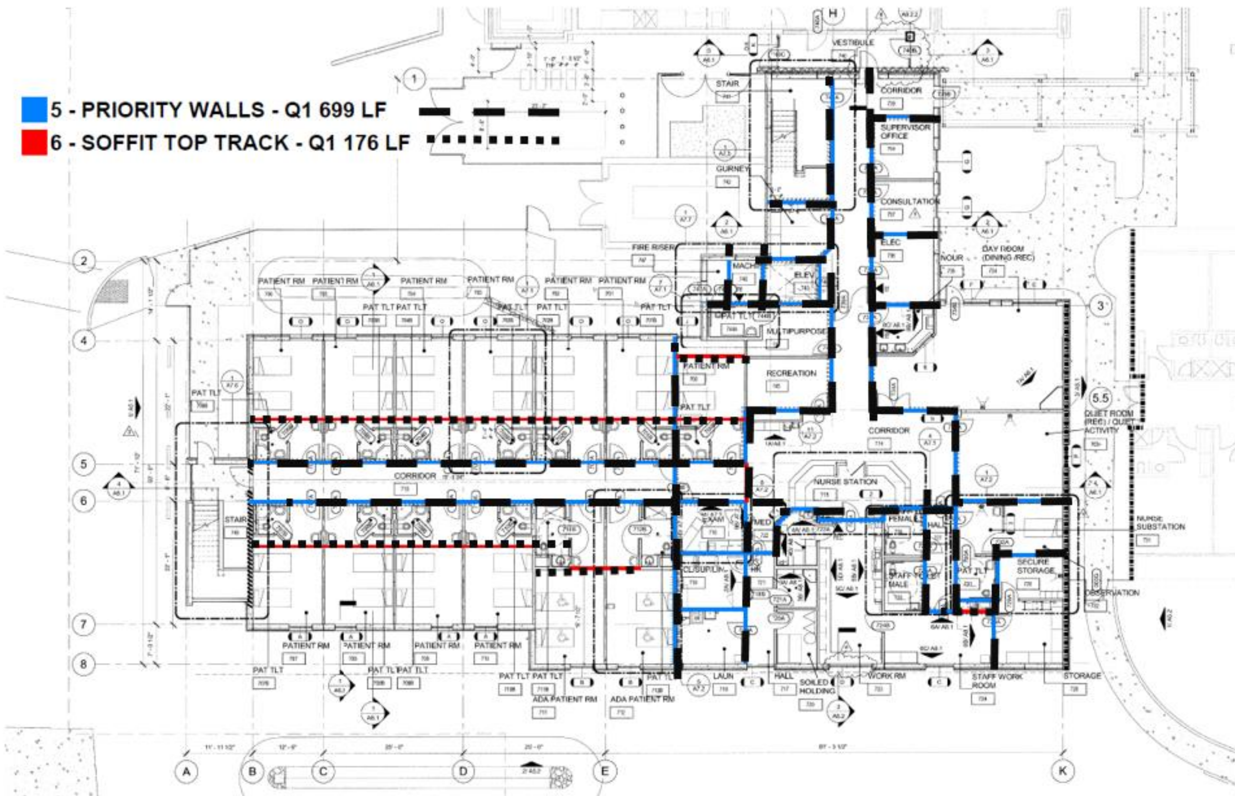


Figure 6-6 – Priority walls for both phases

6.3.2 REDEVELOPMENT OF PHASE 2 TAKT TIME PLAN

Phase 1 start was delayed because the pre-cast panels took four weeks longer than scheduled to complete erection, primarily due to constructability challenges. The exterior wall panels contain stirrups spaced as close as 1-1/2" with steel plates and large rebar bends. If there is any discrepancy between what the OSHPD inspector observes on his detailed plans and what is performed and physically possible at the prefabrication plant, the work stops until the issue can be resolved. If the resolution is not found quickly, all subsequent on site construction is impeded. A total of 23 exterior panels had to be cast in 18 days to meet the construction schedule.

To meet the project deadline, the team analyzed different scenarios for the Takt time plan in Phase 2 produced by the researcher. The plan released Phase 2 comprised of 13 patient rooms per floor, as a single batch for each floor. Figure 6-7 presents a summary view of the different proposed schedule alternatives to complete the work on time. The alternatives keep the same activity sequence as Phase 1, but split Phase 2 work into different batch sizes, or move through the space in four days instead of five (the initial state). Not all of the work in the phase could be split, so the calculation of smaller batch sizes and faster Takt times was not a strict arithmetic calculation (i.e., 10 days of work for an activity does not necessarily equate to five days of work for one-half of the floor, due to the work density). The team added an additional day of work to the total amount of work in the smaller batches to accommodate some of the production variation. It is unclear how much the additional day truly buffered the work and was mainly used as a compromising tool with the production team (the team was trading off smaller batches with faster handoffs, for individually going slower through the space).

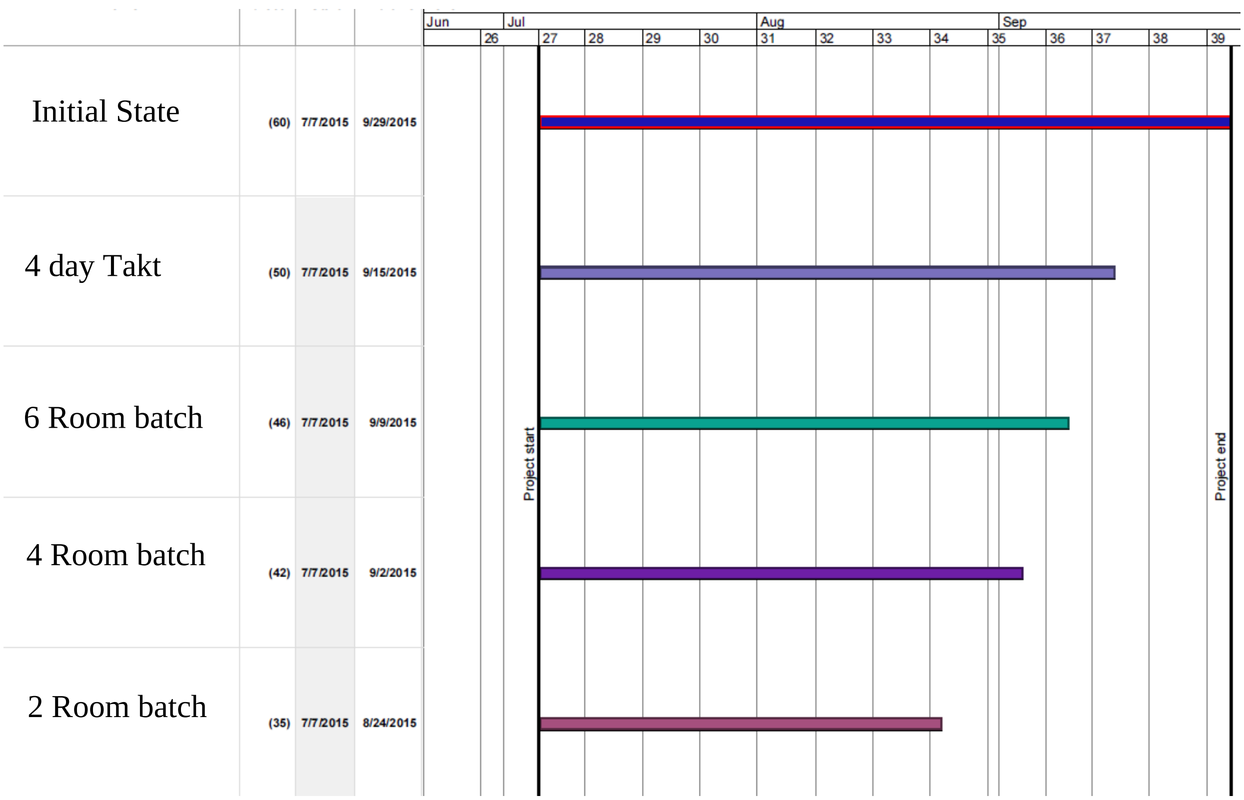


Figure 6-7 – Summary of Takt time alternatives

Table 6-1 highlights the differences in schedule durations for each scenario. Despite the additional day of work added for each activity, the schedule still improves 42% by releasing work in two-room batches. Each activity is effectively going slower (i.e., taking longer per room than a large batch), but the project was paced much faster. The nature of smaller batches also provided a better schedule improvement than speeding up each activity by 20% (from five days down to four) with additional manpower or changing the work methods. Thus, a schedule will improve overall with decreased batch sizes.

Scenario	Total Duration	Total Improvement
Initial State	60	0%
4-day Takt time	50	17%
6 Room batch	46	23%
4 Room batch	42	30%
2 Room batch	35	42%

Table 6-1 – Summary of scenarios

The proposed scenarios effectively communicated to the production team the schedule benefits of smaller batches of work. The production team identified that the corridor work should be split from the patient room work because the work contents, pace, and sequence of the corridors were different than the rooms, and if such small batches were going to be used, this was the only way to make the batch sizes feasible. The team established activity sequences for the corridors, sequences for the patient rooms, and the handoff of the entire space from the 'corridor parade,' to the beginning of patient work in the production meetings. The foremen provided crew sizes and durations on a per room basis. The work was paced by the initial trade partner, the plumber, moving through the space. The plumber worked through the space at a rate of two rooms per day, and was the slowest trade to move through the rooms. The milestone for starting finish work determined the Takt time and batch size. The method for selecting the batch size in this case was set by the lower limit of space (two rooms) through which the plumbing trade partner could feasibly work. Thus, the Takt time for Phase 2 was one day.

Working through the smallest batch possible was counter to what the trade partners initially requested (i.e., the zones used in Phase 1). However, several circumstances changed on the project that may have enabled and/or necessitated the option to move through smaller batches than the phases. First, the team members were working through the building and could physically see the space (including its size, as well as physical and logistical constraints). Second, the demand rate had increased such that the initial Takt time plan for Phase 2 was no longer feasible, so either the team would have to move through smaller batches of work, or everyone would have to move through larger ones at a faster rate. To hit a comparable approximately six-week duration for the scope of work, the team would have had to adopt a three-day Takt time for the entire space. It is not an impossible feat, but it would have required more resources and rapid material movement into the building to accomplish.

6.4 Results

6.4.1 Phase 1 Takt Time Results

During Phase 1, the trades did not execute the work as planned, due to issues related to a pre-cast shaft opening for the vertical duct work. The space was so large that the shaft wall could not be framed, as there was no concrete. Without concrete, there is nothing to attach the top and bottom track to, preventing some tasks in the first production activity sequence (vertical work/fire sprinkler rough install) from starting as planned, while other activities progressed. A better Lookahead process may have caught the opening conflict with the framing, but the project circumstances resulted in little time between pre-cast panel erection, pouring the concrete floors, and the start of MEP layout. As such, the earliest time to realize the problem may not have provided the team enough time to solve it before it constrained work because it was a field condition.

Figure 6-8 provides a supplemental way to view the construction activities. The figure assigns a number to the activities in the construction schedule that the team tracked via the Weekly Work Planning meetings by order of planned start. The planned and actual starts for each tracked activity are displayed. The planned starts come from the Takt time plan the team created together. The actual starts come from the Weekly Work Plan data. Though the chart does not depict a complete picture, it does visually identify which activities slipped more than others, and may provide insight into which activities should be examined in more detail. The average activity started 3.9 days later than planned, and the standard deviation for the activity starts was 16.2 days. The longest delays came from the work left out due to the shaft challenges. The actual shaft installation work was delayed 50 days, and the overhead plumbing installed afterward was delayed 28 days. The soffits and ceilings left out due to the shaft were delayed 28 days as well.

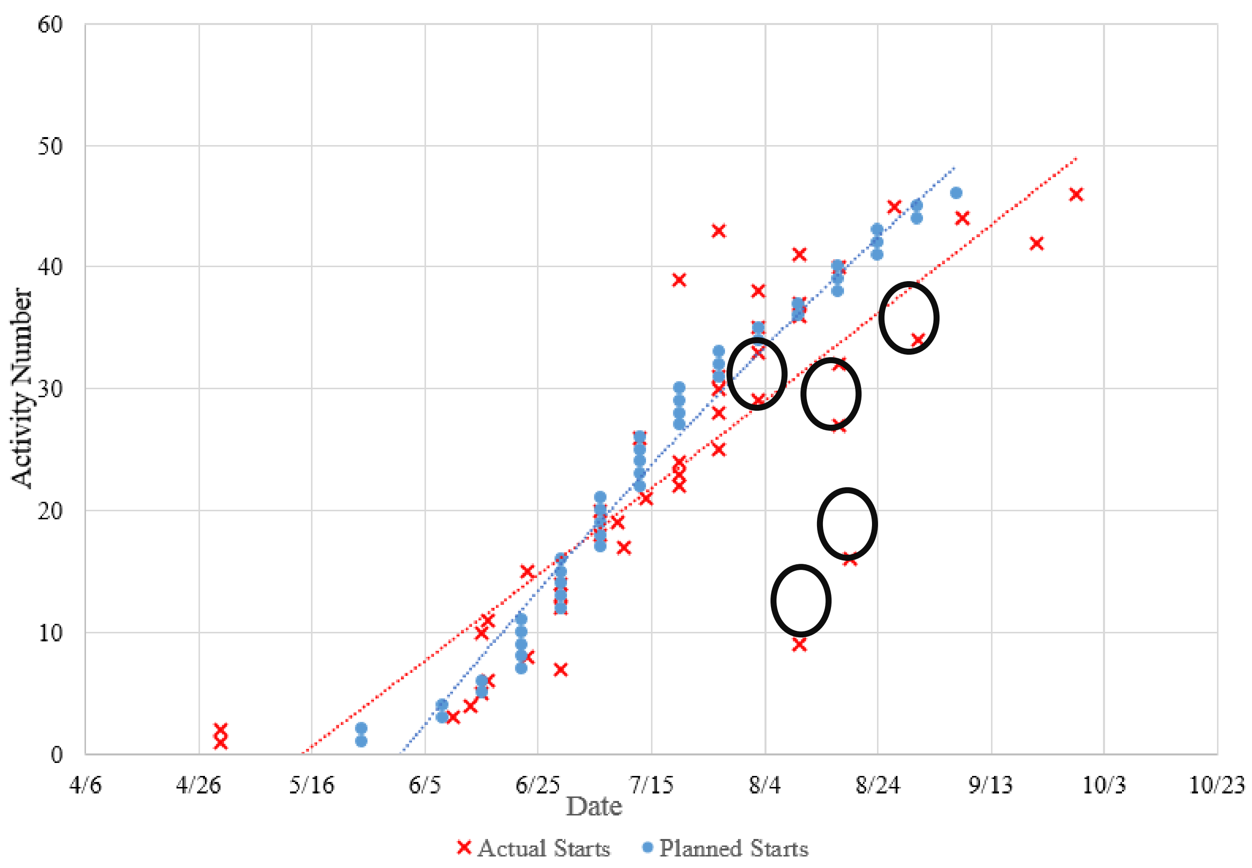


Figure 6-8 – Phase 1 activity starts (circled activities are shaft work-related)

6.4.2 PHASE 2 TAKT TIME RESULTS

Production tracking for the patient room work was performed weekly. The researcher produced the daily production plan, Weekly Work Plan, and colored floor plan that were all posted in the field on the first floor by a project engineer (Figure 6-9). Instead of reviewing production at every daily huddle, the team went straight to identifying problems in the field, where the problems were tracked in an issue log and labelled on a floor plan with stickers. This helped the team solve problems, but did not help the researcher collect production data.

Figure 6-9 – Field Production Boards

Figure 6-10 reflects the production plan for Phase 2 for the first two weeks of work, and provides a sample of what the overall planned work looked like. Each activity is represented by a colored box. The completion date for the room is shown along the top of the figure. The activities crossed out by the diagonal line were completed as planned. This was a simple method to track production. As shown, Room batch 1 on July 29 was not completed due to a dimensional issue with the framed walls. The conflict impacted inwall plumbing, and the test and insulate tasks. Figure 6-11 shows the corresponding floor plan designated the zones (the two room batches) that the activities worked through at a one-day Takt time.

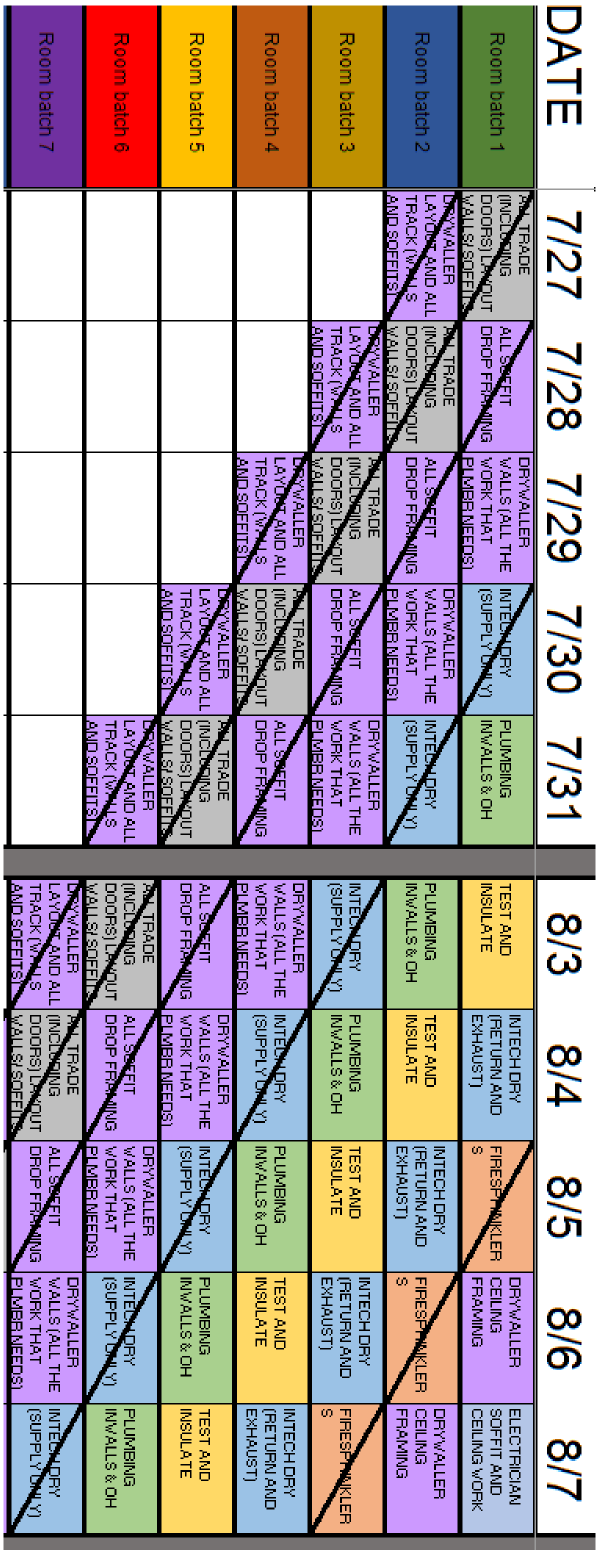


Figure 6-10 – First two weeks of the updated Phase 2 Takt time plan (the lines through boxes represent completed work)

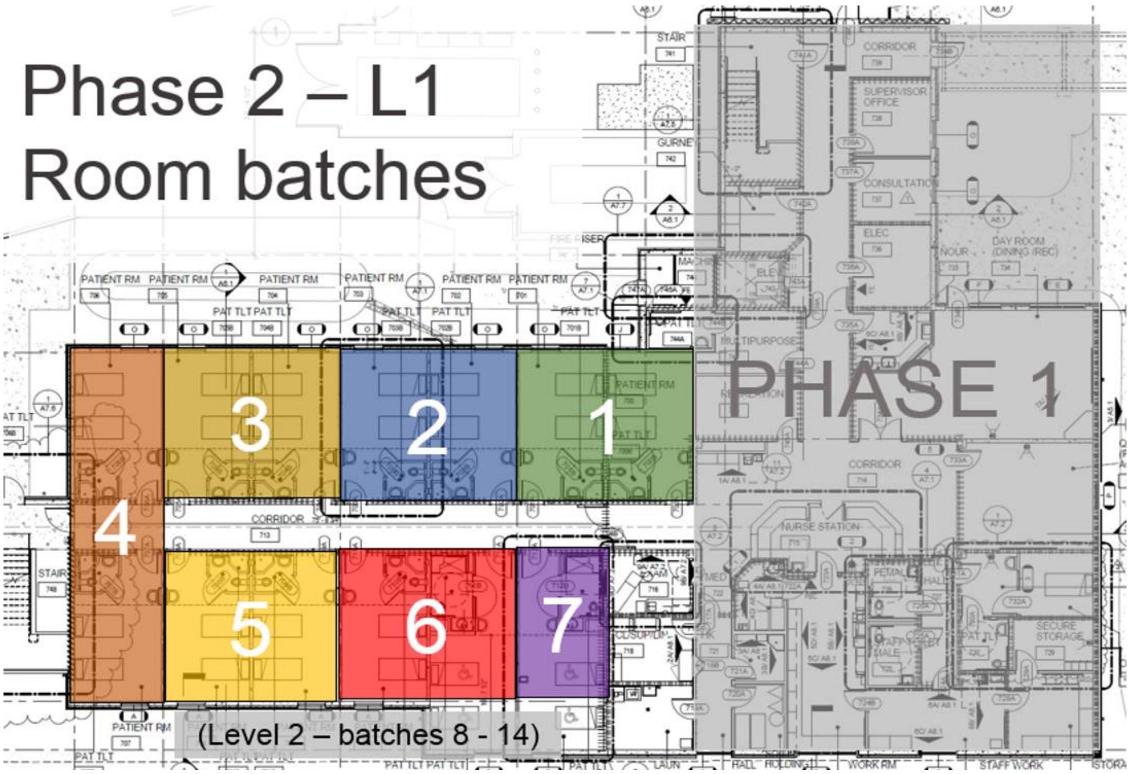


Figure 6-11 – Updated Production Floor Plan for Phase 2

Thus, the Takt time plan was not followed because of the mentioned dimension issue in the framed walls. The work still progressed, because the network relationships between activities did not exist in all locations. Upon further inspection of the work contents, the supply side duct could proceed before the walls were framed, but not before the soffit drop framing. Furthermore, the return and exhaust duct could proceed even though the inwall plumbing was not completed in every room. The fire sprinkler work could also proceed ahead of schedule in the Takt time plan without blocking out the space for the remaining trade activities. Thus, work was able to proceed, even though it was not in the planned and preferred sequence.

Three weeks into Phase 2, after delays due to dimension issues and field conditions varying from the modelled work, the team began to track daily production via field color-ups. The work was tracked in field meetings by marking up what was done and what the team planned to accomplish the following day. The initial proposal was to create these color-ups in the Weekly Work Planning meeting, but the team preferred to create them day-by-day in the field to communicate all the work that was handed off every day caused by previous leave out work. A majority of this leave out work came from the shaft duct leave out in the initial Takt time plan. Other leave out work was generated because the Trade sequence in a particular zone was different than the Takt time plan indicated and what the team assumed. This stresses the importance of checking activity sequences for all zones.

Phase 2 framing and plumbing changed due to dimension conflicts. Some of this delay was absorbed through restructuring the work. An unintended consequence of the delay was that it reduced the number of passes required by the framer, which in turn reduced the number of passes for the electrician through each patient room, and saved two days of work per room. However, the actual execution for the work was still longer than planned due to the time required to produce and approve design solutions for the dimension conflicts.

The restructuring of the Phase 2 sequence negatively affected the insulator, HVAC crew, and plumber. The insulator needed to insulate plumbing after the ceiling soffits were framed in a few rooms, which were in tight locations. The decision to move the insulator after framing was made in order to keep the framer more productive and avoid an extra work pass of framing. Plumbing was more difficult than planned, because concrete grinding around the vertical pipes passing through the slabs was required. HVAC was also more challenging to install because the pre-cast block outs were not in the same area, nor were they the same size as in the model. The result was that duct was sometimes double stacked (i.e., one duct physically stacked on top of the other) through holes in small locations. In addition, duct also conflicted with top track for soffits in some patient rooms. Using First Run Studies would theoretically be a method for resolving these types of production challenges related to mechanical work. However, circumstances were specific to the unique characteristics of the patient rooms; thus, a single first run study would not capture all of the production challenges.

6.4.3 PROJECT PPC

Figure 6-12 presents the PPC for the field activities and Make Ready plan for the project. As a general note, the “skew” in the data comes from availability of the data, and when the team started tracking the different plans. The average field PPC was 63% before Takt time planning started on the project, 73% for the Takt time planning work, and 63% during the finishes when Takt time planning was abandoned. The average Make Ready PPC was 64%. The Make Ready PPC plan contained specific non-field activities for the designers, project engineers, owner, and project managers. The team generated activities on the Make Ready plan when it screened construction activities weekly, and identified specific activities that needed to be done to make the work ready (e.g., create and send drywall trade the elevation for the west wall of the north stair). The intent of splitting the Make Ready Plan activities from the field was for organizational purposes. Figure 6-13 is an example of the activities in this Make Ready plan. The researcher did not network the activities to the construction activities; thus, there was no direct tracking whether an activity on the Make Ready plan affected a construction activity if it was not completed. As such, the team members mentally tracked whether activities on the Make Ready plan affected construction, and planned work on the Make Ready plan accordingly.

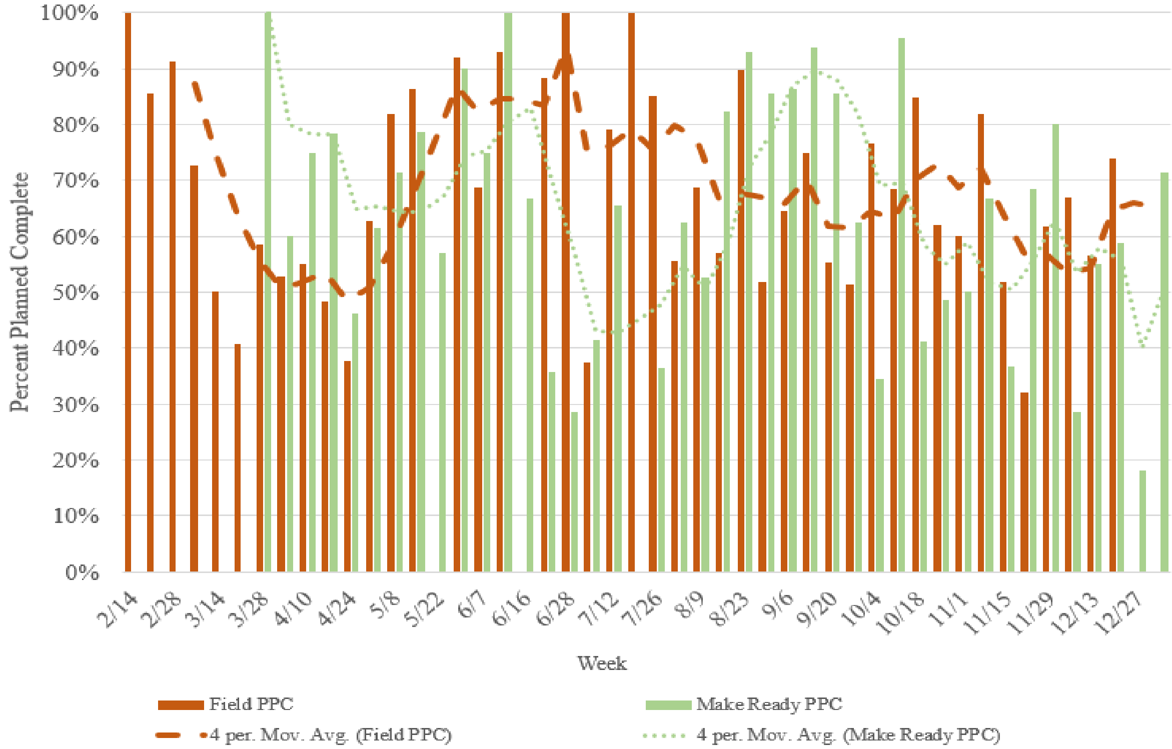


Figure 6-12 – PPC for Field and Make Ready plan over the course of the project

Task Description	Start Date	Duration	Notes	Finish Date
Revised struct deck welding schedule for elevator decking (Issue 53/RFI 42)	7/21/2015	1		7/21/2015
New duct penetration into isolation room. %*()* reviewing and to provide approval/documentaion.	7/21/2015	1		7/21/2015
Team agreed to swarm the exterior brick/window sill issue and resolve quickly.	7/21/2015	1		7/21/2015
Sound caulking for MEP and FP. Will determine location and requirement.	7/21/2015	1		7/21/2015
Need ACD's where imbeds are missing (elevator guid rails, mech screens, etc.). @#$*& provide as-built info to @#$&.	7/21/2015	1		7/21/2015
RFI#36 need to issue ASI.	7/21/2015	1		7/21/2015
Complete I2 existing analsysis for issuance to team.	7/21/2015	1		7/21/2015
Provide option to change out door hardware in existing facility for code compliance. #$& will complete A3 and work with $#*& to prepare ROM budget	7/21/2015	1	See Item 31 Duplicate issue	7/21/2015

Figure 6-13 – Example of Make Ready plan activities

The relationship between the Field and the Make Ready work was surprising. It makes sense that if the work is not being made ready (i.e., there is a low Make Ready PPC), then the Field PPC would decrease. However, there is no correlation between the two values. Nor is there a correlation between the PPC of the Make Ready plan and the following weeks' PPCs in the Field.

One explanation for why there is no correlation, is that people simply do not commit to do work they know is not ready in a given week. Instead, they "make do" and work on something else that ends up on the plan, but this is no longer the Takt time plan. As such, there may not be a correlation between the PPC values for the Field and the Make Ready plan. A production relationship certainly exists between the Make Ready work and the field. The field activities will not be completed if the work is not being made ready and the actual schedule figures reflect that relationship, where some activities started much later than planned.

A second explanation is that the team was not adhering correctly to the Last Planner System, and that impacts the data. If the team connected the Make Ready activities to the construction activities, the data could be further refined to test a correlation between the Make Ready activities immediately affecting construction and the Field PPC.

Overall, the project finished three months behind schedule. While Takt time planning produced a schedule that could meet the requirements, the team was not able to realize that schedule. While the plan was not able to be realized, the cause for the inability to follow the plan appears to come from the upstream capacity to make work ready. The following discussion section explored this notion, which also became the inspiration for the simulation in Chapter 7.

6.5 DISCUSSION

6.5.1 STEP ZERO – TARGET AND MILESTONE DEFINITION

Takt time planning started on this project with some top-down milestone planning, which helped set a target demand rate for a given work phase. This was not observed in the other case studies on Takt time planning, and should be considered a step or an initial sub step in the data collection. Understanding the demand rate is critical to aligning the project requirements with the production means.

6.5.2 OBSERVATION ON TAKT TIME – CHANGING THE PLAN

While facing the four-week delay and seeking solutions, the general superintendent challenged the implementation of Takt time plan with the question: how can we improve? Due to the nature of compartmentalizing the work into batches and pacing the entire flow of the project, the work could only move as fast as the batches in front of it. Furthermore, if multiple activities were going on within a batch, the work could only go as fast as the parallel activities. This is a result of choosing to pace work to fixed Takt times, and challenges current practice that opts to start activities early if possible.

Two answers provided a path forward from the superintendent's question. The first was that the Takt time was set so that it meets the demand of the project. If the current Takt time does not meet the demand which increased due to the delay, the team should create a new plan. The second was that if plans are in constant flux, strict Takt time plans may not be the right method of work structuring for the project. However, if the project does not demand the faster schedule and the plan is stable, it may be more cost effective for the crews completing work too fast to slow down and use less manpower. This is precisely what a Takt time plan aims to achieve.

A broader conclusion related to this observation is that Takt time planning will reveal problems related to poor design, improper look ahead, and production estimates, but should reveal them without affecting the integrity of the production plan. Some plan failures require design changes that are more catastrophic to the production plan, and require areas in the Takt time zones to be left out, as well as additional work passes. One counter measure is to accept this situation and create multiple work passes; in future Takt time planning implementation, this could be a potential change. A second counter measure could be to create a time buffer in the Takt time plan after the layout tasks to identify issues, and allow more time for design to resolve issues prior to production activities that are buffered with capacity. This counter measure is discussed further in the succeeding section.

6.5.3 DESIGNING FOR PRODUCTION

The architect commented that one of two shafts was omitted in design while he was away on vacation, increasing the work density for all of the mechanical in the area with the remaining shaft, and decreasing it in the area where the shaft was removed. Later in this case study, the pre-cast openings were too large for the shaft wall, and the Takt time plan was negatively affected because all early duct out of the shaft needed to be rescheduled. If there were multiple shafts, the risk of an incorrect shaft opening (independent of cause) and halting all shaft-related activities would have decreased.

This problem is similar to another challenge faced in system coordination. MEP detailers and coordinators often solve conflicts between components at a local level. Whatever the cheapest solution is at that immediate location, or whatever causes the least redesign is the solution a design team will use. If an overall production strategy were understood in design, the design team would better understand the effects they were having on production sequences of the entire project. This would also enable the team or a researcher to collect data on production problems that are preventable through design, those that design cannot solve immediately, and those requiring further research (Boothroyd, 1984).

6.5.4 LOOKAHEAD AND TIME BUFFERING

A reflection on the project and the Lookahead process emphasizes the importance of all trades performing a screening of work as soon as possible. From the mechanical trade partner's perspective, the shaft looked fine because there would only be an issue if the shaft opening was too small. From the framing trade partner’s perspective, there was a constructability issue that required immediate attention, but the problem was caught during the layout activity, and would not be resolved for over a month.

One method of maintaining the Takt time plan in future cases such as this would be to create a time buffer between field layout and the start of production activities. The time buffer would have to be sized to provide the amount of time necessary to remove the potential constraints identified in the field. If design integrity is not necessarily trusted, the quality requirements are strict, and the BIM is not complete, so it may make sense to add a time buffer into the Takt time plan to provide time for the team to devise new design solutions. This is not an ideal solution, for it adds to the overall project duration in theory, but it may enable a more stable production system overall that would complete faster than if no time buffer is used.

The intent of using an early time buffer would need to be clearly communicated to the entire project team to avoid building reliance on the constraint identification method. This is despite the fact that identifying constraints in the field while executing an activity may not provide enough time for the office personnel to remove constraints, depending on the Takt time and capacity of the office team to create solutions. Nevertheless, layout is an effective time when the field can identify problems; however, the real production system questions to ask are when is the earliest time possible to check field dimensions (that the layout is correct and feasible) to identify these potential constraints, who needs to check, and what needs to be checked?

6.5.5 DESIGN CAPACITY

Combined with having a strong Lookahead process, this project highlighted the importance of having the design capacity to resolve problems. This will be explored more in the simulation. A strong Lookahead process accurately screens activities before they start in the field. If the design capacity is not aligned with the Takt time plan, the bottleneck can move from the field to the office. If this occurs, it may be better for the project to use time as a buffer, rather than capacity. Due to the flexibility of interior MEP work, often the field team can work on workable backlog (non-critical tasks) or adjust activity sequences. As such, the field team is working to a plan that is different from the one developed during the Takt time planning process.

If the Takt time plan could not be followed, does that mean the Takt time planning process was wasteful? The process and the plan still do more good than harm to a project, for the Takt time planning process reveals production assumptions, paces the production system, and helps to reveal problems and bottlenecks prior to and during construction. If the initial plan contains discontinuous work, unlevelled activities, or incorrect schedule assumptions, it is more challenging to distinguish between problems that are production problems, versus those resulting from a flawed schedule. Thus, Takt time planning allows a project team to better understand the challenges of pacing work in environments without repetitive work contents.

6.5.6 PHASES AND ACTIVITY SEQUENCING

The Phase 1 Takt time plan was the 14-activity sequence described in Figure 6-5 from pre-cast erection's handoff of the space, to the beginning of finishes. The inwall and overhead MEP rough installation sequences were combined into one parade. This was a unique work structure compared to the other case studies, due primarily to the pre-cast walls containing some MEP roughed-in. This is an example of how design affects the work density and the set of schedule alternatives. The work density was affected because the patient rooms (Zone A) were pre-cast walls, and zones B and C contained framed walls. In the other case studies, overhead MEP activities required more space and moved more quickly than inwall MEP activities. Here, the team agreed that both could move at the same pace.

6.5.7 COMPARING DURATIONS BETWEEN INITIAL AND PLANNED

The Takt time planning process started with pull plan data that did not result in a feasible schedule. It was not clear to the researcher why the team had not iteratively worked on their pull plan to meet the milestones. The project team did see Takt time planning as a means to produce a schedule that would be feasible. However, it the pull plan could have potentially not been updated because the Takt time planning process would integrate the data anyway. Indeed, through Takt time planning, the team collaboratively found ways to structure work into a 14-activity sequence that adjusted total schedule durations required by each trade (Figure 6-14). Note that framing did not have any work initially in Level 2 Phase 1, but this changed during the planning process. A rationale for these deductions is that the foremen gained a better understanding of the work involved, the environment, sequence, and project requirements from the Takt time planning process. Changes in crew sizes would also affect the data, but the initial schedule data was not resource-loaded, so performing this analysis was impossible.

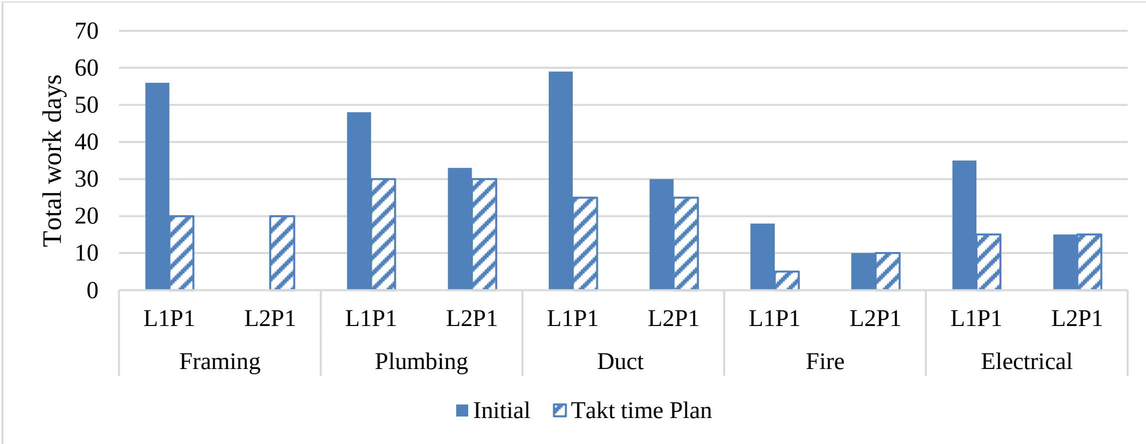


Figure 6-14 – Changes in durations from initial pull plan to Takt time plan (L1P1 = Level 1 Phase 1)

6.6 Case Study Conclusion

This case study on the interior MEP build out of a psychiatric care facility expansion reflects the findings and lessons learned regarding how the Takt time plan was developed and executed in two work phases. The phases contained the MEP trade rough installation work from the handoff of the space from pre-cast, through the drywall taped and finished. On this project, Takt time planning began after a pull planning session held before the researcher joined the project. The Takt time planning process started with the realization of the need to develop a schedule for the interior MEP work that would complete within the owner requirements. The Takt time plan developed through weekly production meetings that followed the Takt time planning process is described in section 6.3. Some differences in the process compared to the other case studies came from the project circumstances: the research started with planning data the team later refined, and the demand rate required a much faster Takt time than the initial durations. Confirming the initial durations with color-ups was an effective exercise to understand how the team could work/move together at the necessary pace.

The case study offers many lessons for future iterations of Takt time planning. Takt time planning emphasizes the need for effective Lookahead processes. If production problems are revealed during the Takt time and cannot be solved within it, the plan is bound to fail and will require adjustment. Though the team could not execute due to upstream constraints, the case study also demonstrates how Takt time planning can help a team increase their throughput by rethinking the production process (e.g. 6.3.2) and increasing the batch size. Furthermore, if production problems are understood but there is no available designer capacity (or the solution has an approval lead time longer than the Takt time), a production bottleneck will form in the office. If that is the case, it is likely favourable for the project to use more time buffers than capacity buffers. Understanding this trade-off could be made possible via discrete event simulation.

CHAPTER 7 CASE STUDY 3: PAMF DANVILLE PROJECT

7.1 INTRODUCTION

This chapter presents a case study of Takt time planning developed for the construction of medical office building interiors in Danville, California. Unlike other projects in this research, this project was not required to meet OSHPD code. The Danville project is a two-story build out in an existing wood-framed, 14,000 ft^2 (1,300 m^2) facility. The owner of the project is Sutter Health, a large non-profit health care provider in Northern California. The architect on the project was SmithGroupJJR. The construction manager and general contractor was Layton Fernandes. The project was delivered via a Guaranteed Maximum Price (GMP) contract with hard-bid subcontracts and no shared savings.

To fulfil the owner's request to use Takt time planning, the team chose to use the method for structuring the interior MEP build out due to the speed of the construction schedule and the potential to align the MEP activities to the same Takt time and zone sequence. Takt time planning was used for the interior build out from overhead MEP installation until the start of finishes (the taping of walls). Unlike the other case studies, this project set targets for four phases of interior work to which the team would align its activities. This chapter covers the development, results, and lessons learned with respect to implementing Takt time planning on the project.

7.2 CASE STUDY TIMELINE

Figure 7-1 presents the timeline of the case study from April 2015 to December 2015. The project team played the "Parade of Trades" game in the kickoff meeting. Individual meetings with the trade partners to understand their scopes of work and individual requirements succeeded the game in the following week. At the end of May, the team had a finalized contract schedule (development discussed in Figure 7.3.1). Structural and demolition work began on July 1, 2015, and the entire project was finished and ready for the owner to begin moving in on December 1, 2015. The interior work was released by the structural activities floor by floor. Pull planning of the work determined the necessary activity sequence from layout to ceiling close-up. As an initial goal for the team, the superintendent and researcher structured the work into four phases with targets for floor completions based on the Reverse Phase Schedule meeting data and the owner's demand rate. The Takt time planning work was completed during the first week of November.

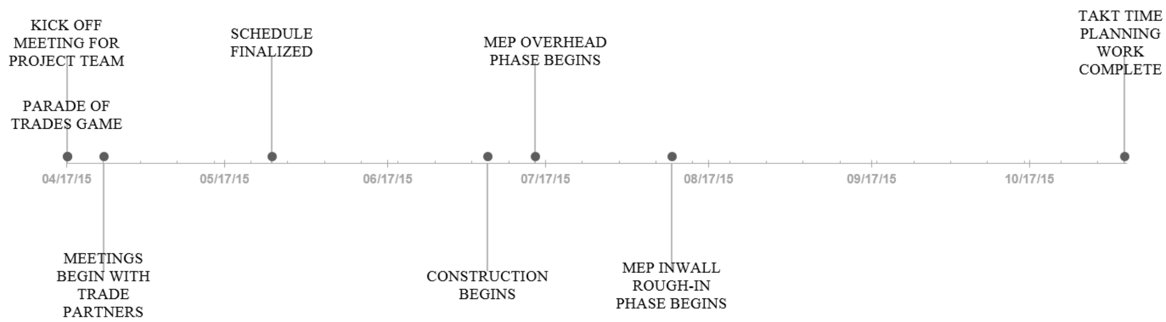


Figure 7-1 – Case study timeline

7.3 Initial Work

7.3.1 Development of Takt Time Plan

Production planning started with obtaining buy-in from the subcontractors to use Takt time planning. The project team (general contractor, subcontractors, and owner) played the "Parade of Trades" game to demonstrate the importance of reliable handoffs and the effects of variation in production systems. No one on the project team had previous training in the Last Planner System, or experience with Takt time planning. The researcher's advisor scheduled meetings with the plumbing, electrical, and mechanical contractors to understand their individual scopes of work and specific production considerations. The meetings were held at the subcontractors' home offices. Following these meetings, a Reverse Phase Schedule meeting was held to discuss all of the work, from wall layout through close-up of the ceilings. At this meeting, there was also a discussion regarding whether the owner required the building in January or in December. The rationale for these boundary conditions is that these were the approximate boundaries for the scopes of work bought out, and contained the majority of work performed by the MEP trades.

Figure 7-2 shows the floor plan of the first floor of the medical office building. The middle rooms not touching the perimeter walls are mostly patient rooms. The west side of the building contains the elevator, front entry, lobby, and stairs to the second floor. Each floor was approximately 7,000 ft^2, or the size of the entire project in Case Study 1.

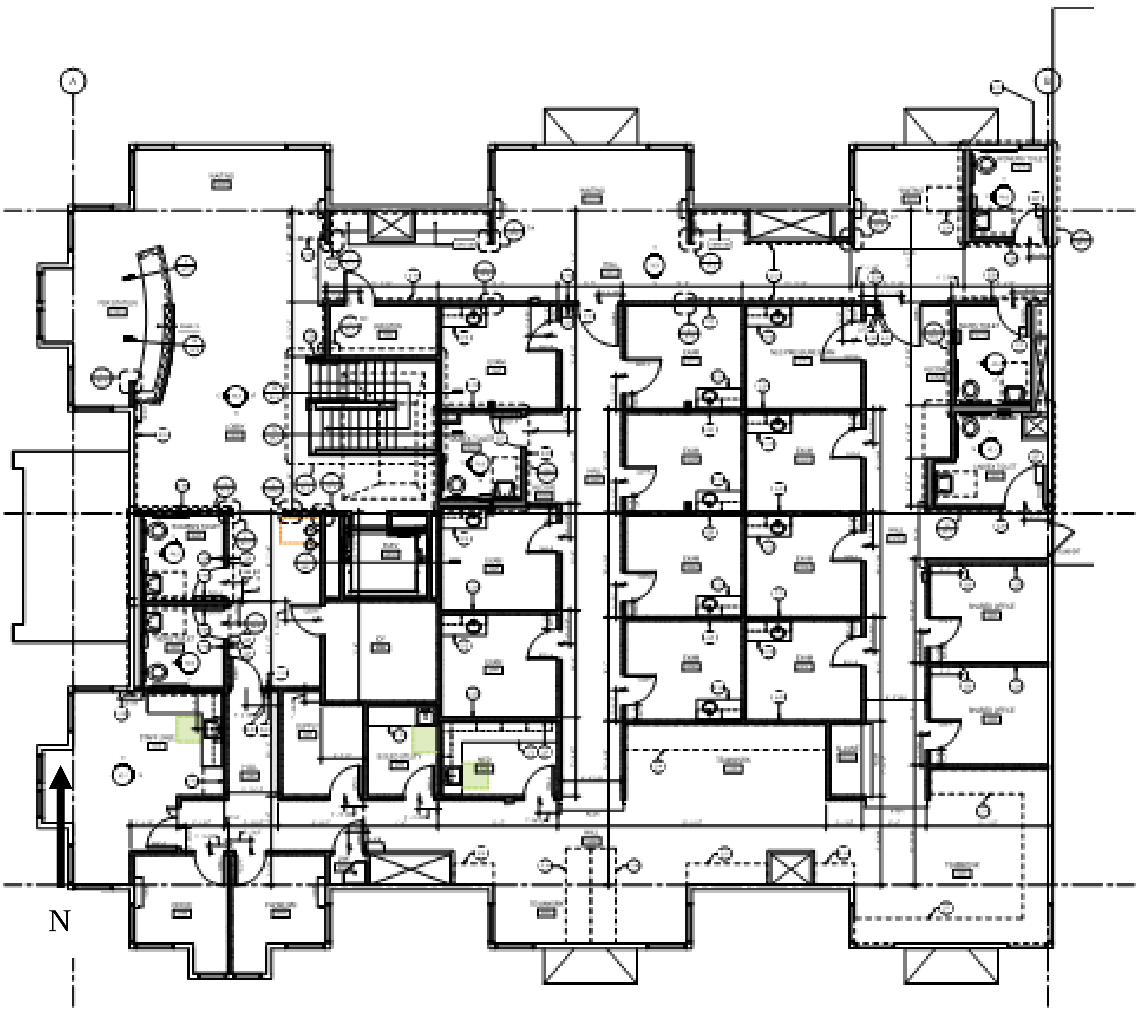


Figure 7-2 – First floor of the PAMF Danville Project

In the individual meeting following the kickoff meeting, the plumbing contractor started with an overview of their scope of work. Attending the meeting were the plumbing superintendent, foreman, and company owner who discussed floorplans, sequence, and manpower. The plumbing design came from an outside engineering company with whom they frequently worked. First, they needed to complete underground work in a crawl space directly under the first floor. There was uncertainty about the crawl space height under the floor and access holes, so no durations were provided for this work at the time. Next, they preferred to work their way up the building from the center out to the perimeter, starting with the first floor, followed by the second floor. They had work on the roof and considered it workable backlog because it did not hand off work to others, and they could complete it around their other work inside the building. Discussing manpower, their superintendent commented that the most efficient way to staff a project this size was to have one plumber perform all the work. After the meeting, it was still unclear if their intent was to staff the project with more plumbers, or stay with one through the project.

The electrical contractor project manager and foreman attended the electrical contractor meeting. The electrical contractor first provided an overview for their scope of work, involving installing a new meter for utilities, performing main power distribution work, conduit and wiring the new equipment on the roof, and installing all lighting, power, and low voltage work. They decided to subcontract the low voltage work. The electrical contractor also helped with design. The foreman said he required a four-man crew to complete each half of a floor (i.e., two areas) in 10 days in the overhead and inwall MEP sequences. Thus, the total approximate desired man-days across two floors for the two phases was 320 man-days (4 people x 2 floors x 2 areas x 10 days x 2 phases).

The mechanical subcontractor started with outlining their scope of work. The project manager, project engineer, and foreman for the project, as well as their engineering manager, piping foreman (who changed during execution) and foreman installing the controls attended the meeting. The mechanical subcontractor was also contracted to design the mechanical system. Their scope of work involved installing the mechanical equipment, duct, roof equipment, mechanical piping, and controls for the HVAC system. Their preferred work sequence was to start after all of the structural retrofitting and fire sprinkler work was complete, and begin with installing the main duct work, known as the "HVAC race track." Because the wood structure had little area (approximately three feet, or about one meter) above ceiling and the trusses took up a majority of the space, the mechanical contractor opted to use flex duct that would branch off of the HVAC race track to provide for additional flexibility (compared to fabricated non-flex duct) during construction. Following duct installation would be the piping work, insulation, and plumbing. The mechanical subcontractor did not have a preference for which floor to start, but did prefer to work from east to west across the space, working towards the main entrance side of the building so material did not need to be moved past installed components.

The mechanical subcontractor also considered roof work as workable backlog. However, they also acknowledged in this meeting that some of the roof equipment had long lead times, and it would not be possible to finish their scope of work if equipment was ordered when the final construction contract was signed. Identifying this was a critical finding project and the general contractor worked with the owner and mechanical subcontractor to ensure that these items could be separated from the contract and accelerated, to avoid delaying completion of the project.

The project team engaged the drywall subcontractor later than the MEP subcontractor, after the meetings with the MEP trades. This meant that the drywall subcontractor's input was not obtained early enough in the project to affect the initial planning and contract schedule in May. Instead, the superintendent approached the drywall foreman when he first arrived on site in order to get his opinion on the schedule. The drywall foreman said his company elected to use 20-gauge steel frames throughout the building, instead of optimizing the framing steel required in the design, and buying the lighter gauge steel in areas where it was allowable. This allowed the framer to only order one gauge type of studs for the entire project. In addition, 20-gauge steel is much lighter and easier to drill screws into because it's thinner than the 16-gauge steel required on OSHPD 1 projects. The benefit is that the hanging and framing tasks performed by the drywall contractor can be performed faster with improved ergonomics due to the lighter material. The foreman planned on having himself and one other carpenter during framing to maintain the pace of the project. He also commented that he was amenable to zones smaller than half of a floor if necessary, and if he needed to release work faster, it would not be difficult to get more carpenters on site.

After understanding everyone's desired sequences, workflows, and scopes of work, the researcher worked with the superintendent to develop different schedule proposals. The researcher scheduled the alternative scenarios in a Line of balance (LOB) format to understand the feasibility of different options to meet the owner's desired project completion date. The schedules contained production targets for four phases of work per the superintendent's request: overhead MEP installation, rough in-wall installation, above ceiling finishes, and the finishes phase of construction. Typically, the above ceiling finishes phase is combined with the finishes phase due to the similar pace at which the work progresses, but from experience with ceiling inspection processes, the superintendent wanted this work to have its own phase. The superintendent set targets for each phase of work (five weeks per floor during overhead MEP rough-in, five weeks per floor for inwall MEP rough-in, eight weeks per floor for above ceiling finish, and eight weeks per floor for finishes), and the researcher generated several work schedules, each with different assumptions (e.g., splitting the floors in halves, working multiple crews, working Saturdays, etc.).

Figure 7-3 contains a summary in Gantt view of the different work schedule scenarios. The smallest zone size for any of the scenarios is roughly 3,500 ft^2, which is one-half of the floor space, because the trades were not amenable to working in a space any smaller. One might question if the reason why they were not amenable was due in part to contract structure, and how they were incentivized to maximize their efficiency.

The final construction schedule was based on Scenario 6: one crew through two zones (per floor) while working Saturdays. There were two reasons for choosing Scenario 6. First, the team was not comfortable working through smaller zones than one-half a floor. Second, the owner updated their requirement and asked for construction to be completed on December 1, and because the team thought working with one crew and Saturdays was more feasible than getting all of the subcontractors to run two crews on the project. The schedule used the sequence established from the trades' input during the RPS meeting.

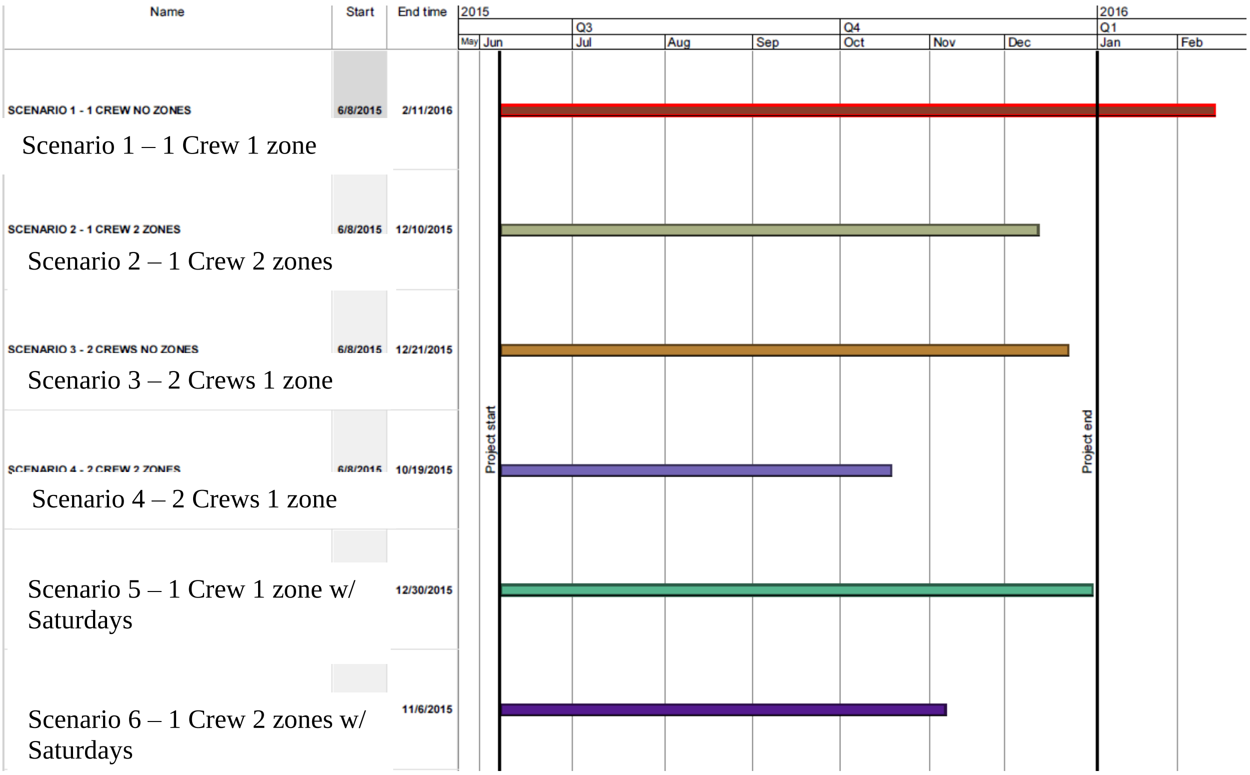


Figure 7-3 – Schedule Scenario Summary

Figure 7-4 reflects a summary Gantt view of the final contract schedule. Some of the summary bars contain gaps representing work discontinuities for the activities in the phases. This does not mean work is not occurring, however, as there are multiple construction phases occurring simultaneously on site. Changes between Scenario 6 and the actual schedule came from confirming the schedule assumptions (i.e., start date, how many activities require space to themselves, activity sequences, inclusion in the appropriate phase, etc.). The elevator work was ongoing through the overhead, inwall, and above ceiling phases, but it did not affect how the flow of that work was scheduled. Not finalized with the team until the start of construction due to uncertainty in the structural work, was the actual work sequence through the zones. The team previously expressed their sequence flexibility for different tasks in the individual meetings, so they agreed to delay the decision on the zone sequence.

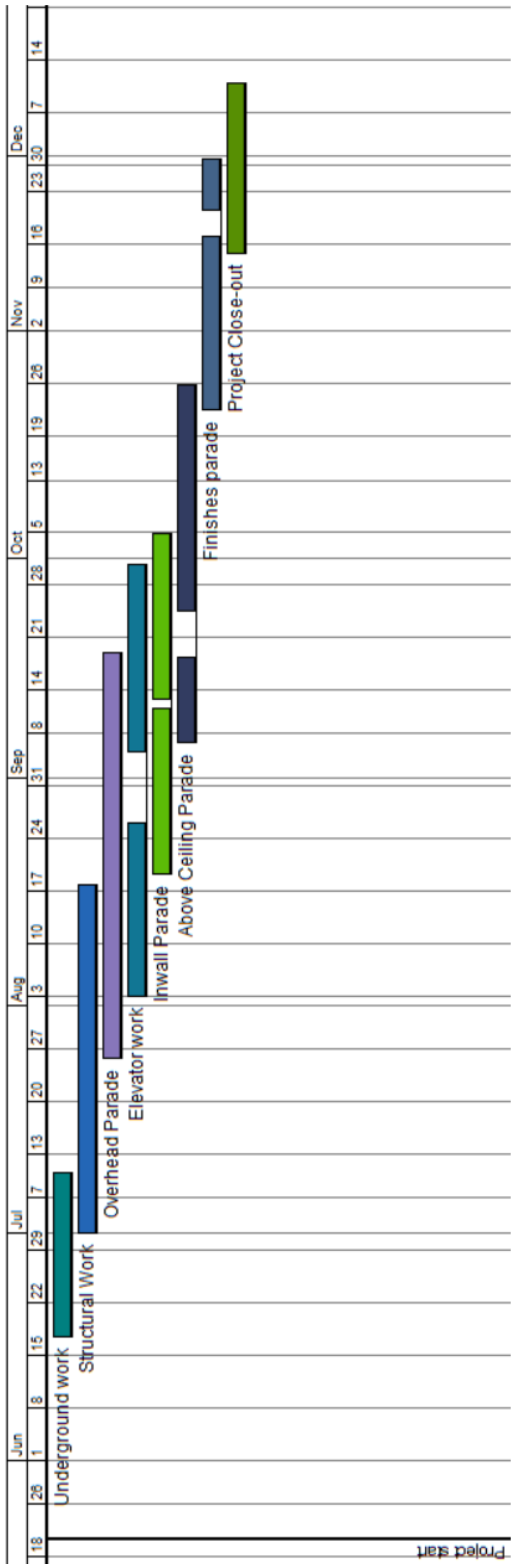


Figure 7-4 – Summary view of entire Danville construction schedule

7.4 RESULTS

The structural work phase became more understood once it started and the team established the zone sequence for the remaining interior work. The zone sequence was to start interior construction on the second level on the east side of the building, then move down to the east side of the building on the first floor, followed by the west side of the first floor. This sequence was influenced by how the structural and elevator work needed to be performed on the west side of the building (Figure 7-5). All activities could flow in this sequence, except the vertical plumbing work that needed to begin on the first floor (Figure 7-6).

Figure 7-5 – West side of building opened up for elevator/structural work

Figure 7-6 – Plumbing work start on first floor (see plumbing material, half of which is on a rolling plank)

The work proceeded approximately, but not exactly, to the plan. Due to their sizes and space needed, the crews proceeded in a more parallel fashion (Figure 7-7) and the MEP trades were able to share the space and closely coordinate their work in the field. The work was coordinated in informal daily meetings and the weekly Last Planner meeting. Since the team had not used the Last Planner System, the researcher provided some coaching and discussed the expectations and (briefly) philosophy behind the system. The process for coordinating work was driven in part because there was no coordinated BIM model for the project. The rationale was that it was an existing space, and it likely would have required more effort to accurately depict, design, and coordinate a model, rather than design 2D plans and coordinate the work in the field.

A lesson was that while Takt time planning usually requires only one trade in a space, the assumption is that each trade needs space to itself to be most effective. Thus, when trade crew sizes are minimal (1-2 people), allowing another trade in the 3,500 ft^2 area will not necessarily reduce their productivity, although this would be against Takt time planning practice. Allowing multiple trades in the same space due to small crew sizes may work for production; however, it still requires coordination with the entire team for material storage, logistics, and daily production planning.

Figure 7-7 – Parallel fashion of work; wall framing, electrical, and duct install are nearly simultaneous due to crew sizes and space availability

With a new understanding of the requirements for trade activities, the production plan progressed by maintaining the targets created by the superintendent for the four phases on site, and acknowledged that some of the initial assumptions (one trade per area and only produce work that releases work to others) in the RPS meeting and initial Takt time plan were disproven in the field. The weekly work planning meetings drove the Lookahead process in the work phases. These meetings helped individual foremen to screen upcoming activities; the team tracked any constraints on activities. The researcher also observed that the inspection requirements were not as strict as the other case studies in this research, likely increasing the reliability of the production plan.

Figure 7-8 presents the PPC for the project. The average PPC was 75%, with a standard deviation of 15% and a slightly negative trend towards the end of the project. PPC was calculated weekly, and completion was credited to a task if it would finish in the given week without affecting the handoff to the succeeding trade. As an example, the team held the weekly work planning meeting on Wednesdays. If a task planned to complete on a Thursday, but actually completed on Friday without delaying its successor, it was credited as a successful completion. Typically, this will inflate the PPC for a project, but if movement in a finish date does not affect the successor, this project team assumed that this variation was trivial and they didn't track it. However, if the team ran at a high PPC of 90%+, the researcher would have coached the team to start tracking the handoff accuracy to the day.

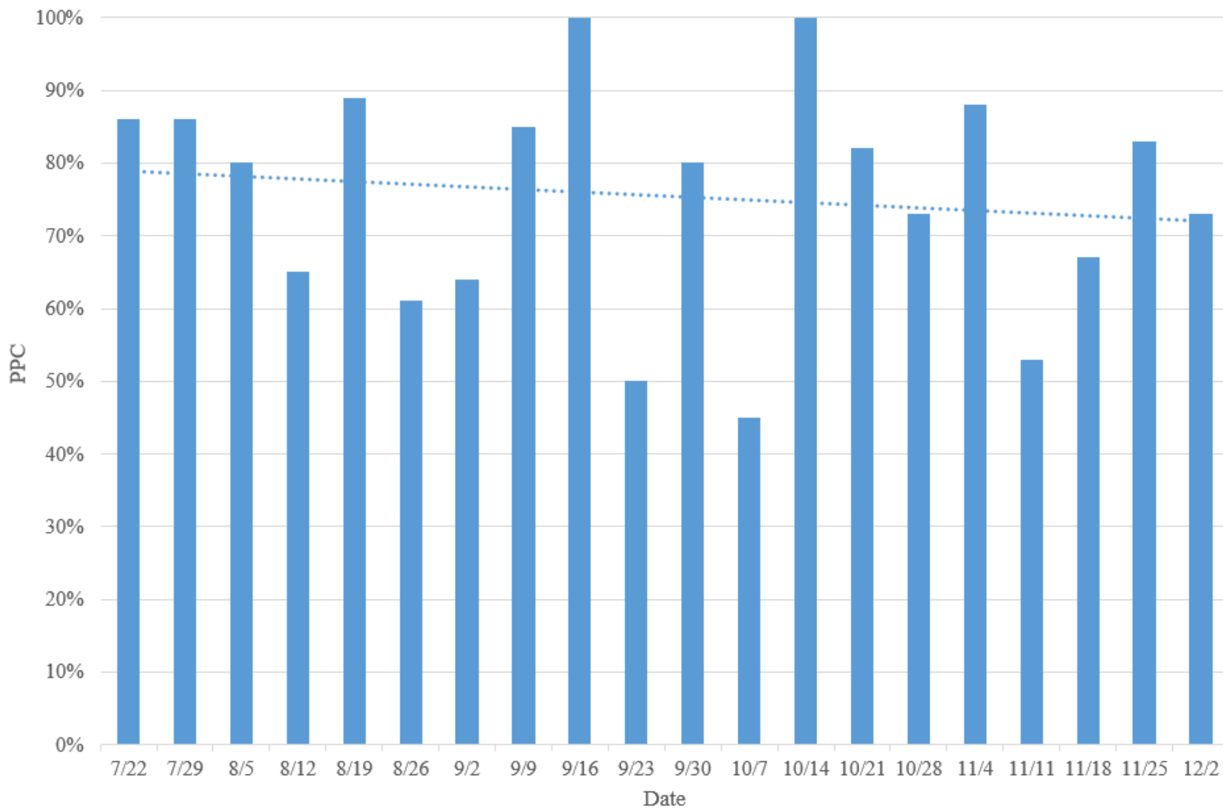


Figure 7-8 – PPC for all construction activities for PAMF Danville

Figure 7-9 presents the planned, versus actual activity starts for all of the construction activities. The planned starts came from the construction schedule created by the researcher before construction started. The actual starts came from the weekly work planning data. Overall, the activities executed according to plan, as the team met the completion date. However, activity starts varied by an average of 1.8 days and a standard deviation of 16.3 days. The activities furthest off were the thermostat control activities, which started roughly 50 days later than planned. One reason for this inaccuracy was that these activities were not pull planned with the subcontractors' input because they were contracted through the electrical subcontractor. Regardless, that work was not production work (i.e., it involved one or two individuals connecting thermostats, and did not immediately release work to others), so the inaccuracy did not impact the project end date. If the thermostat-related work is omitted, the average actual start decreases to 0.14 days from the planned start, with a standard deviation of 11.19 days.

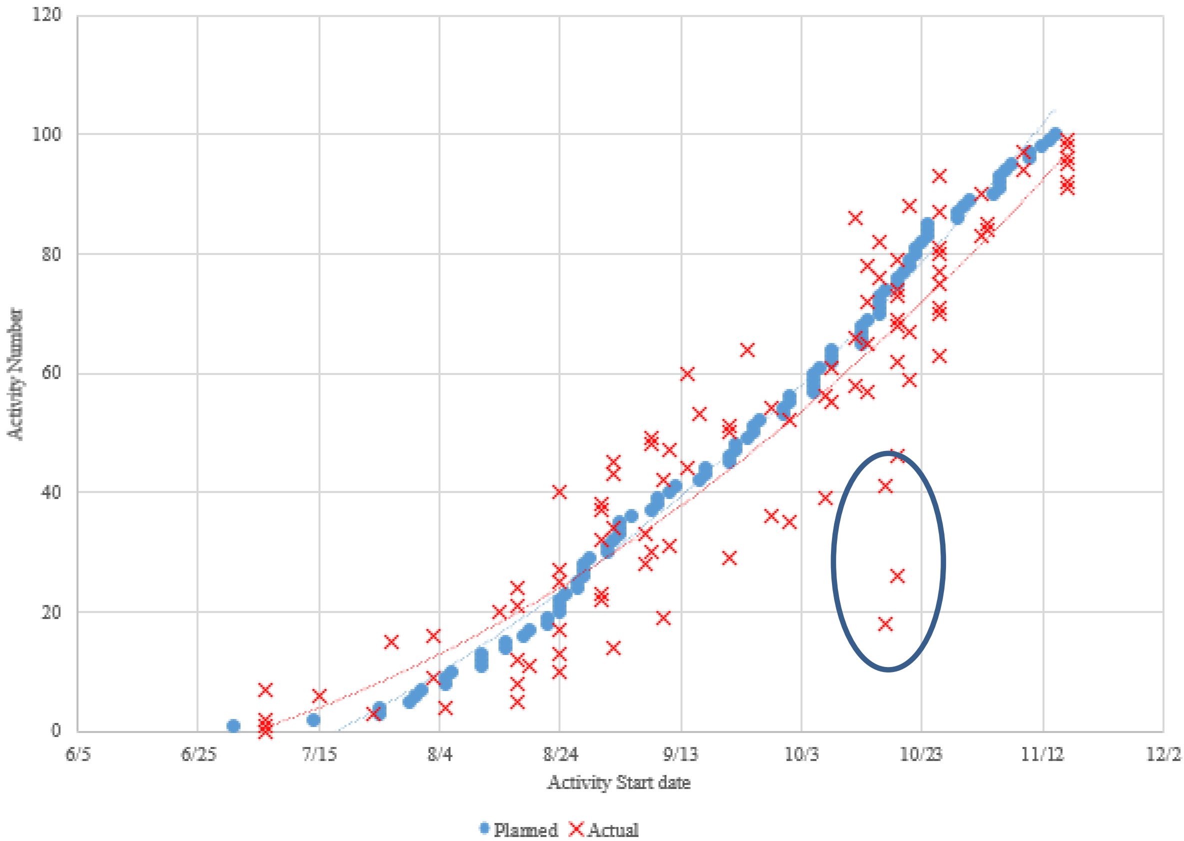


Figure 7-9 – Planned versus actual starts of all construction activities (circled are the thermostat activities)

The project was a financial success; it carried an approximately 10% contingency that was returned to the owner. Because Saturday work (a total of 26 Saturdays) was incorporated into the schedule, an additional $157,000 was allotted to cover the accelerated schedule (overtime work). This additional money came from the summation of each subcontractor's estimate of their overtime costs, with Saturday work included. The general contractor tracked overtime work on a single cost code. The team completed the work using only $36,000 (23%) of the overtime budget. However, this cost code was also used for any overtime, including unplanned overtime (e.g., someone needed to stay past eight hours to finish work). Thus, the savings in overtime is conservative because it includes Saturday and unplanned overtime during the week. The schedule contained approximately 144 construction days, including 26 Saturdays. Assuming the overtime use equates to six (23%) days of Saturday work required, the time savings due to not working planned Saturdays is approximately 20 days, or 14% of the construction schedule.

7.5 DISCUSSION

7.5.1 FIELD VERSUS BIM COORDINATION

Unlike the other case studies, this project did not have a coordinated BIM model. Field coordination ensured reliable handoffs and prevented conflicts between components. This was also the first time the team used the Last Planner System. Nevertheless, the pacing of the project provided people with time to look ahead at their work, collaborate, and solve problems.

Figure 7-10 shows a field coordination problem the foremen worked through as a team. The issue was identified and resolved in the field by the plumbing foreman, electrical foreman, and site superintendent. Light fixtures and copper plumbing were conflicting in the design documents, so the plumber moved pipes for the fixtures. Not shown in the picture is the other end of the ceiling, where the joists moved up slightly higher. Because the ceiling joists moved up, the conflict did not carry across the floor. The varying ceiling joist heights could be an initial cause of the conflict (i.e., a designer did not notice the change in ceiling joist height), but the team was unable to confirm with the design team why the conflict existed.

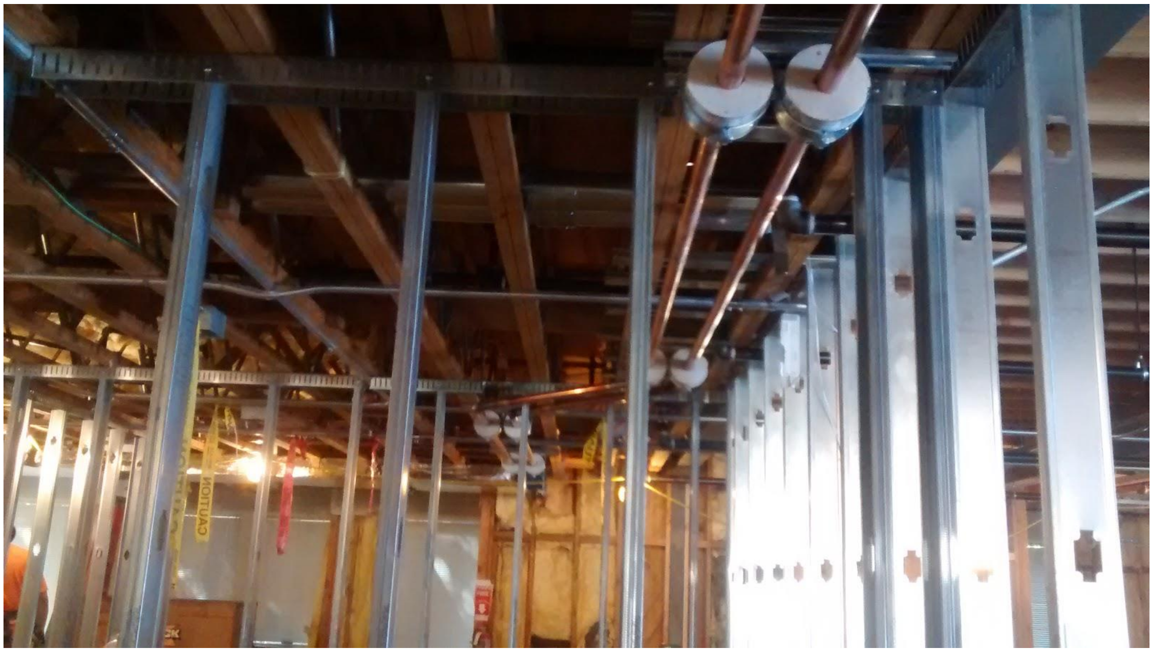


Figure 7-10 – Electrician and plumber field coordination

The decision to field coordinate versus producing a coordinated BIM model was due to the project characteristics. The building was wood-framed and built a few decades ago. The ceiling space above the joists was very tight (less than three feet), and accurately capturing those dimensions in the model would have been difficult. As shown on Case Study 1, laser scanning an existing building does not ensure that the environment is accurately captured, especially when it is not clear which components the general contractor needs to demolish. Figure 7-11 shows an example of the overhead space. All of the MEP work had to fit in roughly three feet of vertical space, with trusses spanning across the floor every three feet. With work weaving in, out, and around the trusses, coordinating the work in the field appeared to be the faster, more accurate, and cheaper solution. This solution requires flexibility in component locations. If every component had to be installed in a precise location (i.e., as would be the case on an OSPHD project), field coordinating may not have been viable.

Figure 7-11 – Example of tight overhead space

The wood framing in the existing building was a blessing and a curse for the mechanical subcontractor's production system design. The close conditions above the joists forced the use of flex duct, which decouples the work from the other systems in the space, and allows for easier field coordination around other MEP work because it can move freely (assuming there is space) around rigid components. However, lots of flex duct requires higher static pressure (thus, larger and more expensive air handling units) to push out the same air volumes.

7.5.2 IMPLEMENTATION OF TAKT TIME PLANNING

The project did not execute perfectly to the Takt time plan. While developing the plan, the researcher assumed that every trade would need the space to themselves while working in a zone. The size of the zones, crew sizes, and need to coordinate work in the field invalidated this assumption in execution. As such, the overall targets for each of the four phases were followed and controlled in the weekly work planning meetings, instead of checking that the strict Takt times through the areas for every activity were followed. Understanding when this assumption applies is important for future implementations of Takt time planning.

While the Takt time plan was not perfectly followed, the process was still valuable to the project in many ways. Talking with the hard-bid subcontractors early, before the construction schedule was created, revealed procurement challenges that required early buy-out (e.g., of the roof skid) if the project was to be completed on time. Understanding how the different trades needed to work through the space enabled the development of a feasible production schedule that satisfied the owner's deadline. In addition, this early information allowed the superintendent to plan the work efficiently. For example, after understanding what work needed to be done by all trades on the roof, one Saturday morning was planned to crane lift all of the work, as opposed to multiple lifts on multiple Saturdays. Early conversations with subcontractors help to build the relationship with them. Taking into consideration their thoughts on the project shows a genuine effort for collaboration and respect for their work.

Working with this team revealed additional considerations for Takt time planning. The "lower boundary" of the zone sizes was set primarily by the comfort level of the subcontractors. The contract structure may or may not have influenced this comfort level. In theory, the contract affects the comfort level because a lump-sum contractor is financially incentivized to reduce the cost of their own work, and nothing else. However, subcontractors still face a similar incentive on an IPD project, and unless they buy into the idea and trust that the smaller zones (that can translate into faster speeds of project delivery) will produce the desired outcome with a higher likelihood than a larger zone size, they will opt for the larger zone size.

7.5.3 Design Capacity and the Lookahead Process

This project did not calculate a separate PPC to track the Make-ready work, primarily because there was no need to do so. In the weekly Last Planner meeting, the foremen and superintendent would discuss constraints that would be tracked, and the project had an Owner/Architect/Contractor (OAC) meeting the following day to resolve them. Design only affected the plan in one week, due to designers relocating heavy imaging equipment inside a room that required additional structural support for the raised floor. Otherwise, design did not appear to affect construction. In addition, the researcher rationalized that design and construction on the project appeared decoupled due to the lack of a BIM model, because this enabled the construction team to field coordinate work, rather than coordinate the work in design.

7.5.4 Hard-bid Takt Time Planning

This case study was the first known published experiment of Takt time planning with hard-bid subcontractors. As long as the planning requirements are understood, and there does not appear to be any contractual reason why the subcontractors are opposed to planning and executing to a Takt time plan. One challenge to hard-bid Takt time planning is that the team needs a way to collect input from subcontractors early on, before the contract is finalized, or to provide a Takt time schedule in the request for bids. This would make the Takt time planning process more of a 'top down,' than 'bottom up' process, in which a team would begin by understanding the subcontractors' requirements. In addition, it can open the general contractor up to potential liability if the detailed Takt time plan changes.

7.5.5 Lack of Field Visual Controls

This case study did not use visual controls in the field. The researcher attempted to use them for several weeks, but the project team did not support their use in the field, and they were abandoned. The superintendent did value visual plans and the team used a laminated floorplan to help communicate logistics during the weekly planning meeting with subcontractors. During the finishes phase, the superintendent used a colored plan to help communicate which rooms were a priority for certain finishes (Figure 7-12). The purpose of communicating priorities was that it varied for different trades. The patient rooms needed casework, while the bathrooms required more tile and plumbing finishes. Ensuring that both room types were progressing was important to the project overall. Other than that instance, no other boards displayed plans to everyone in the field.

Figure 7-12 – Example of finishes color-ups

7.6 Conclusion

PAMF Danville was a successful project that brought new insight into Takt time planning. This case study provided an opportunity to test Takt time planning with a non-IFOA team, did not use a BIM model, and tested the assumptions of Takt time planning. Takt time planning began before the contracts were signed with the hard-bid subcontractors. The Takt time planning process came from knowledge generated from the case study at Mills Peninsula. The resulting schedule consisted of four work phases with the same four production zones. During execution, the team disproved the assumption that only one trade could occupy a location at one time due to the zone sizes (>3,500 ft^2) combined with the small crew sizes (1-2 people per crew) and the necessity to field coordinate the work. Understanding when this assumption can be relaxed is important to answering the research question of what flow looks like in construction. As such, the Takt time plan was not strictly followed on this project, but the pacing of work by phase was still met using only 23% of the acceleration budget. In other words, the project went roughly 14% faster, while accruing 77% less additional costs than budgeted for the acceleration. Potential success factors for doing so were the correct matching of design capacity to the project pace, and the project team's ability to coordinate work in the field.

CHAPTER 8 SIMULATION

8.1 INTRODUCTION

This chapter describes the simulation inspired by observations from the case studies. The objective of the simulation is to study the consequences in terms of time and money (and the trade-offs of time and money) from different types of work structuring methods. As discussed in Section 1.8, simulation helps to answer the research questions by providing a means to test and gather data in a controlled environment. The chapter begins with an overview of the model setup, including the model entities, variables, assumptions, and activities. Then the chapter outlines the experiment and sensitivity analysis experiments, and presents the modelled simulation. The chapter concludes with the results of the experiment, sensitivity analysis, discussion of the results, and conclusion.

8.2 MODEL SETUP

8.2.1 OVERVIEW

The discrete event simulation tests different work structuring methods, Takt time planning, a CPM schedule, and an LBMS (i.e., a schedule with time buffers) for the construction of work for a linear trade sequence through a space. The purpose of this simulation is to help answer the second and third research questions (what barriers exist to designing continuous work flow of construction activities and what are the costs/benefits to using Takt time planning). The model divides a given space into four zones, worked through by trade crews in the same order and same trade activity sequence. By simulating different types of work structuring methods through this same order and sequence (e.g., a Takt time plan, using time buffers, a CPM schedule with early starts, etc.) it is possible to understand which variables described in Section 8.2.3 drive the sensitivity between trade-offs in cost and time. Each experiment will also have a Make Ready process to simulate how work is released to the field activities. Experiments from this simulation produce results for an assumed scope of work in time and cost.

Based on observations from the case studies, the tested hypothesis is that certain types of variation are better absorbed with different types of buffers, assuming the variation cannot be reduced or eliminated. By simulating the magnitude and frequency of the different types of variation and their impact on construction, it is possible to study how different time and capacity buffers influence the project duration and cost.

The model for each alternative (CPM, LBMS, and Takt) incorporates a Make Ready function. Before any work activity can start for a trade, it is screened for readiness. If the work is not ready, it moves into a new queue for the non-field team to Make Ready. The non-field team makes the work ready in order to understand how "non-field capacity" during construction may become a bottleneck depending on certain variables. In practice, these people are the designers, project engineers, project managers, and superintendents writing/answering RFI's, approving submittals, procuring material, etc. To track how demand is created in different zones and allow the model to simulate complicated zones (i.e., a higher likelihood of work not being ready), each Make Ready process for the zones is modelled separately, instead of moving all the Make Ready work into one queue.

When simulating the Takt time plan, delays and pacers are used to start the successive trades according to a schedule sequence. A delay is an activity in the model that postpones the start of another activity to a set time. A pacer is a process in the simulation that helps to release work at specific time intervals. The pacer is used to release work at the set Takt time. For example, if there is a five-day Takt time, the completed work is released to the succeeding trade every five days. Thus, the model prevents simulated trades from starting early on activities in zones until the planned time (i.e., before the Takt time sequence begins for an activity). After the delay, the first activity the trade performs is the Make Ready step of discerning between work that is ready and work that is not ready. The simulation is set up such that all the completed work in the previous Takt time sequence is released to the succeeding trade.

Mathematically, the model is structured to enable the work in the zone to be completed within the Takt time with the given crew size with >99% certainty[2]. In non-Takt time planning scenarios, the completed work is released immediately to the succeeding trade. However, the succeeding trade may not begin to start the work until all the work is completed by the previous trade, and may not begin their Make Ready process until the specified percentage of complete work in the preceding activity (set by the user) is fulfilled.

The output of a single simulation is the total duration, labor cost, and individual labor costs for each trade. These individual labor costs are a function of time, crew size, and crew mix. The total labor cost is a sum of the individual labor costs. Using different cost variables for crews, general conditions, etc., this model can translate the output into an expected cost for a modelled scope of work. Assuming the scope of work is critical to the construction project, an improvement of the scope of work translates to a direct improvement in the total project duration and cost.

8.2.2 MODEL ENTITIES

This section details the different entities modelled. Entities may represent something physical and concrete (e.g., a trade crew that will perform work), or something abstract (e.g., a variable representing the amount of work needed to be performed that exists for mathematical purposes) (Schruben and Schruben, 2009). Resident entities exist in the model for a long time. Transient entities 'move' through, or in and out of the model. Understanding what to model as well as what entities are resident and transient helps to define how to model the system.

8.2.2.1 Resident Entities

Non-field capacity – Non-field capacity represents the capacity of the people working on the Make Ready process. It is a deterministic resource variable analogous to the size of a trade crew.

Trade Crews – Trade crews are the teams performing the initial Make Ready work activity of screening (i.e., looking ahead and identifying constraints to performing the work), working, and releasing work to the succeeding trade in the field. This model simulates the interaction of four different trade crews working in a linear sequence (Trade 1 starts before Trade 2, Trade 2 starts

[2] This was confirmed by modeling a single person working for five days with the production duration listed in table 7-2, for five days of work.

before Trade 3, etc.) through a set of four zones in a planned order (Zone 1, Zone 2, Zone3, Zone 4).

Zones – Zones are locations where the trade crews work. One crew works in a zone at a time and releases the work to the succeeding trade. The zones also have a priority, where a trade will complete the available work in the lowest zone number first (i.e., lower zone numbers have higher priority).

8.2.2.2 Transient entities

Work quantities – Each trade has a set amount of work in each zone. The work quantities flow through multiple steps. First, the work is screened to assess its readiness (Figure 8-1). If the work is not ready, it moves to the non-field team to make it ready (Figure 8-3). If the work is ready, the assigned trade crew completes and releases it (Figure 8-2). The released work becomes work quantities the succeeding trade can check for readiness.

8.2.3 Model Variables

CPM – A binary variable to release work as fast as possible or on the Takt time variable (1 is on the Takt time interval, 0 is immediate).

Crew size – Crew size is a model variable set by the researcher. It represents the size of the trade crews in the field.

Labor costs – Labor costs refer to the cost of each crew member on site. It is a model variable set by the researcher. The labor cost may be higher per day in some cases due to a capacity buffer. The trade-off is higher reliability that the activity is completed as scheduled.

Lookahead capability – The Lookahead capability is a variable representing the percentage of work that is ready for the responsible trade to work on when it is screened in the model. This Lookahead capability is essentially the team’s collective ability to produce the resources and information at the time of execution of an activity. The “screening” represents the trade foremen’s last check for readiness (also called shielding the plan).

Make Ready duration – If work is not ready, it must be made ready with a stochastic duration. The duration distribution is the same for all trades in all zones.

Make Ready PPC – The Make Ready PPC is a percent planned metric of the activities performed by the non-field team. Figure 8-1 helps to illustrate what the Make Ready PPC represents. The crew first performs the Make Ready activity that screens the work for readiness. A certain percentage of work is ready on the first screening. If the work is not ready, it becomes a “Make Ready work activity” for the non-field team to work on. The Make Ready PPC represents the percentage of work the non-field team successfully makes ready (i.e., when it gets screened again, it becomes ready). If work is ready and the team can do it, they will commit to it and perform the work. As stated in the assumptions below, if work is not made ready but the trade crew is already on site, it is assumed that the crew will work on workable backlog to absorb the unused capacity.

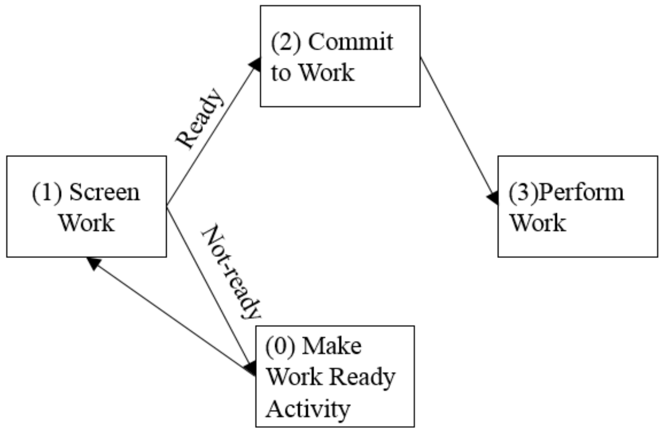


Figure 8-1 – Workflow of modelled Make Ready process

Production duration – Production duration refers to the variation of a trade crew's daily production. The daily production is a distribution set by the researcher.

Percent complete (PC) – The percent of the work completed by a trade in a particular zone before the Make Ready process may begin for the succeeding trade.

Takt time – The Takt time determines how the work quantities change from 'complete' to 'released'. A Takt time of five would result in released completed quantities to the succeeding trade every five days.

TB – A binary variable that designates the use of a time buffer (TB=1) or not (TB=0).

Time buffer between trades (called 'time delay') – The time buffer between trades refers to how the activities are scheduled. There may or may not be a time delay between when the trades start working in an area to decouple the network relationships (and the related duration variations of the networked activities). The delay is a fixed variable specified for each activity within the model.

Work Quantities – Work quantities represent the total number of 'man-days' required to perform work in a given zone by one trade. All trade work quantities are provided in the same units: man-days.

8.2.4 Model Activities

Make Ready – A Make Ready activity separates work quantities for a given trade in a single zone between ready and not ready work. Make Ready activities are those performed by a project team upstream from construction (i.e., looking ahead, removing constraints by writing/answering RFI's, ordering material, double checking the documents for feasibility, etc.). For simplicity, the model checks how well the team performed at making work ready (using the Lookahead capability variable).

Work – Work activities occur in every zone for every trade. Work activities take ready work and create complete work. Work activities require the related trade crew to perform the activity (i.e., Trade 1 work requires the Trade 1 crew). The work activities are prioritized to a specific sequence of zones; after every work interval, the crew searches for the highest priority work to perform.

Release – Release activities move the completed work and release it to the succeeding trade. For example, a wall has been constructed and released to a different trade to install windows in the wall; a piece of equipment has been installed and released to a different trade to install power or control devices. However, precedence can be of different types. For example, an interior wall may need to be constructed prior to installing ductwork, simply because it would be impossible to construct the wall after the ductwork is installed. Or fire sprinkler piping may need to be installed prior to ductwork because the ductwork would impede access to the ceiling.

Make Ready NFWork – Work identified as not ready moves to a not ready queue that non-field capacity mobilizes to work through at a stochastic duration. The not ready work is then completed and moved to the ready work queue with a certain reliability known as the "Make Ready Percent Planned Complete." At the end of the Make Ready work, if a percentage of the work is still not ready, it moves back to the not ready queue.

8.2.5 MODEL ASSUMPTIONS

This researcher embedded several assumptions in the model presented in the succeeding section.

- The first trade can perform all the Make Ready process for their work at once. The remaining trades can only start their Make Ready when the work is finally released to them. This is a simplification from reality and may ignore some dynamics where early work is made ready by using some non-field capacity, but the model still captures the dynamics of how work immediately released can create Make Ready work a project team needs to resolve (i.e., clashes, work access or design problems, etc.).
- The first Make Ready step when work is divided into ready and not ready takes no time. However, if work is not ready, it does take time and non-field resources to make the work ready.
- No trade creates not ready work that is any more or less complex than other trades. In other words, all not ready work sampling comes from the same time distribution.
- Having more non-field capacity increases the potential for the team to work on more problems simultaneously, but each individual problem still takes the same amount of time (i.e., two individuals do not solve a single problem faster, but they can solve two problems simultaneously). In addition, all problems can be solved with sufficient non-field capacity.
- Trade crews will stay on site, even if there is no work shown on the schedule for them. Instead the trade will work on workable backlog that is not modelled. This assumption is based on the case study observations that crews will stay on site and make do, either on work not shown on the schedule or at less productive rates unless the delay is catastrophic, and they will be starved for work for several weeks.
- Related to the previous assumption, no trades suffer from 'catastrophic' delays in which they are on site, but do not work for several weeks.

- The trades follow the plan if possible (i.e., they will work in Zone 1 before Zone 2 if work is released and available in Zone 1 and 2).

- If a member of a crew takes less than a day for a task, they will start another task immediately.

- Regardless of the work structuring method, the sequence for the work through the zones is Zone 1, 2, 3, 4. In practice, following any of the methods would likely result in different zone structures, but not modelling all three work structuring methods in a similar setup would trivialize the results (i.e., the setup with the smallest batch size would have a major total duration advantage). See Section 9.4.2 for further discussion on how batch size affects the total duration for a parade of trades.

- Regardless of the work structuring method, network relationships are finish-to-start between Trade 1 and 2, Trade 2 and 3, and Trade 3 and 4.

- Network relationships between trades are strict and cannot be broken. This means that trades cannot start work until the work is released by the previous trade and checked for readiness. Furthermore, trades will start work as soon as it is released and ready.

- Crews will mobilize to higher priority areas during the day if necessary, but this does not occur in the model—there is no pre-emption. Thus, it is assumed that the crews will mobilize every day to the zone with the highest priority of work, and remain there until the work is complete for that unit.

- The work successive trades screen for readiness comes from their own queue of work they need to perform in the zone; thus, no rework is performed in a zone after the work is released by the previous trade. Instead, the model accounts for 'rework' in the production duration for different trade activities and the Make Ready duration. However, this maintains the assumption that after the work is complete, the next trade can screen it for readiness. While the model will not track additional rework for an activity, it will simulate how work in place can create additional demand (not additional scope, for this is construction administration work) on the non-field capacity.

- Material costs, while important to a project's total cost, are assumed the same in all work structuring alternatives, so they are not included in cost calculations (the goal is to identify the relative benefits between alternatives). The rationale for this is that the same components need to be installed, regardless of how the project is scheduled.

- The model considers inspection delays from failure as "unmitigated," partly for simplification, but also because an inspection failure is a type of delay that typically only time can solve when it occurs (i.e., an increase in manpower or productivity will not solve the problem). The simplification comes from the assumption that no inspection failure is completely "catastrophic" to the schedule (i.e., it does not create month-long, or longer delay).

- The assumption for the labor cost calculation is that each crew member, regardless of trade, is estimated to cost $200 a day.

8.3 MODEL

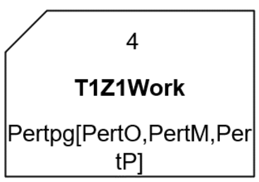
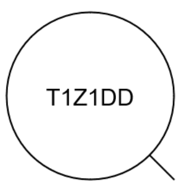
The model was developed using EZStrobe and Stroboscope (Martinez 1996). EZStrobe is a visual, simplified version of Stroboscope. As such, modelling began in EZStrobe and was finalized in Stroboscope. The benefit to coding in EZStrobe is the ability to visually debug the model. For a full description of the model and its entities, see Martinez (1996).

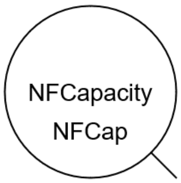
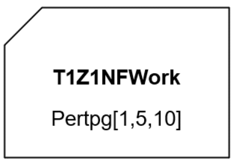
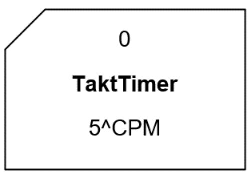
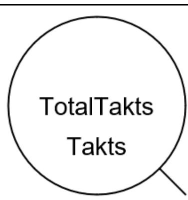
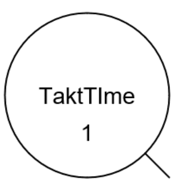
Table 8-1 identifies all the unique model elements. Figure 8-2 shows the model for the first trade going through the first zone. The process begins by moving the screening the work for readiness. This step takes no time, and the work is sorted by a variable called “LookAheadCap.” If work is not ready, it moves into the NotReady queue where the non-field team will have to make it ready. This process is shown in Figure 8-3. The process is a single activity in which some non-field resources are mobilized to perform work with some variation. After the work is completed, it is checked for completion and readiness.

Work determined to be ready moves to the ‘ReadyWork’ queue. If the crew is available to work, the work begins. One crew member works on ‘one day’s’ worth of work. Due to variability, the work takes more or less time to complete than a day. The completed work then increments two queues: (1) T1Z1Complete and (2) T1Z1DD (which stands for “done done” and the need for two different queues was for modelling purposes). The T1Z1DD queue is for tracking purposes and to program network logic into the model. That is, every trade cannot start until the previous trade in the same zone is 100% complete. Figure 8-4 demonstrates this network logic between Trades 2 and 1 in Zone 1. Trade 2 work cannot begin until T1Z1DD equals the total quantities the trade needs to complete in the zone, but they can begin their MakeReady task when the delay is used and the work is completed by a certain percentage ‘PC’ (percent complete). The T1Z1Complete work is released at the end of the Takt time interval, or immediately if Takt time is not used. The control for this release is set with the CPM variable and a pacing process shown in Figure 8-5. Every Takt time, the TaktTimer releases a CPM (0 or 1) to the Work Release queue. If that value is required by the Release activity, the work is released. In this manner, the model is programmed to release the work using a Takt time, or not. When all the work is released, the Work Release queue returns to zero. The model is

programmed to always perform this last by setting the Releaser activity to the lowest priority in the model.

SYMBOL	NAME	EXPLANATION
	T_iZ_jQuantities (in all cases, i represents the trade crew number and j represents the zone number)	This queuing activity represents the work a crew needs to perform in a given zone.
	T_iZ_jMakeReady	This combi activity pulls quantities from T_iZ_jQuantities and sorts them between T_iZ_jReady and NotReady.

	T_iZ_jNotReady	This queueing element represents the work screened for readiness that is not ready.
	T_iZ_jReadyWork	This queueing element represents the work screened for readiness that is ready.
	$Trade_i$Crew	This queueing element represents the "i" crew with the variable number of workers CrewSize.
	T_iZ_iWork	This is the combi activity the $Trade_i$ crew performs on the T_iZ_jReadyWork. The duration of time it takes to complete the work is calculated by the Pertpg formula with parameters PertO, PertM, and PertP. PertPG is discussed further in the experiment section, section 8.5
	T_iZ_iDD	This queuing element represents the total amount of work a trade crew has performed in the jth zone. When this work is all complete, then the succeeding trade can begin to work in the jth zone.
	T_iZ_iComplete	This queuing element represents the total amount of work a trade crew has performed in the jth zone. This work is released to the succeeding trade to be checked for readiness.
	WorkRelease	The queuing element that releases completed work to the succeeding trade every day if it is ready and the CPM variable is 0, or releases the work at the end of a Takt time period if the CPM variable is 1.

	Release$_{ij}$	This combi activity pulls completed quantities for one trade in one zone and releases the work to the succeeding trade, providing that the work is allowed to be released per the CPM variable described in the WorkRelease queuing element.
	NFCapacity	This queuing element represents the non-field capacity on a project team that helps solve problems and makes work ready. The queue is limited by the variable "NFCap" and the capacity is used across all zones and all trades.
	T$_i$Z$_i$NFWork	This combi activity turns NotReady work for the ith trade in zone j if there is available capacity in the Non-field queue to support the activity. Based on the variable "MakeReadyPPC" the work either moves into the Ready or NotReady queue for the ith trade in zone j.
	TaktTimer	This combi activity pulls one unit from the TotalTakts and paces the release of work either at 1 day or 5 days, based on the CPM variable.
	TotalTakts	This queuing element initiates the TaktTimer. If there are not enough TaktTimes then the simulation will not complete work in all areas.
	TaktTime	This queuing element serves as a sink to clear the WorkRelease queue and keeps it empty.
	Releaser	This combi activity pulls released work and moves it to the TaktTime queue so that work is released to succeeding trades at either the end of a Takt time or at the end of every day.

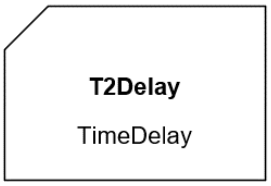
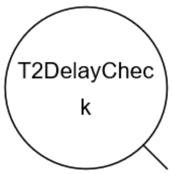
	T_iZ_jDelay	This queuing element is used to pace work in the time buffer case.
	T_iDelay	This combi activity pulls one unit from T_iZjDelay and does not allow the quantity to move to T_iDelayCheck until the deterministic variable duration "TimeDelay".
	T_iDelayCheck	This queuing element is used to pace work in the time buffer case. If there is a unit in the queue and the TB variable = 1, then the MakeReady work for T_iZ_j will not begin.

Table 8-1 – Table of model elements

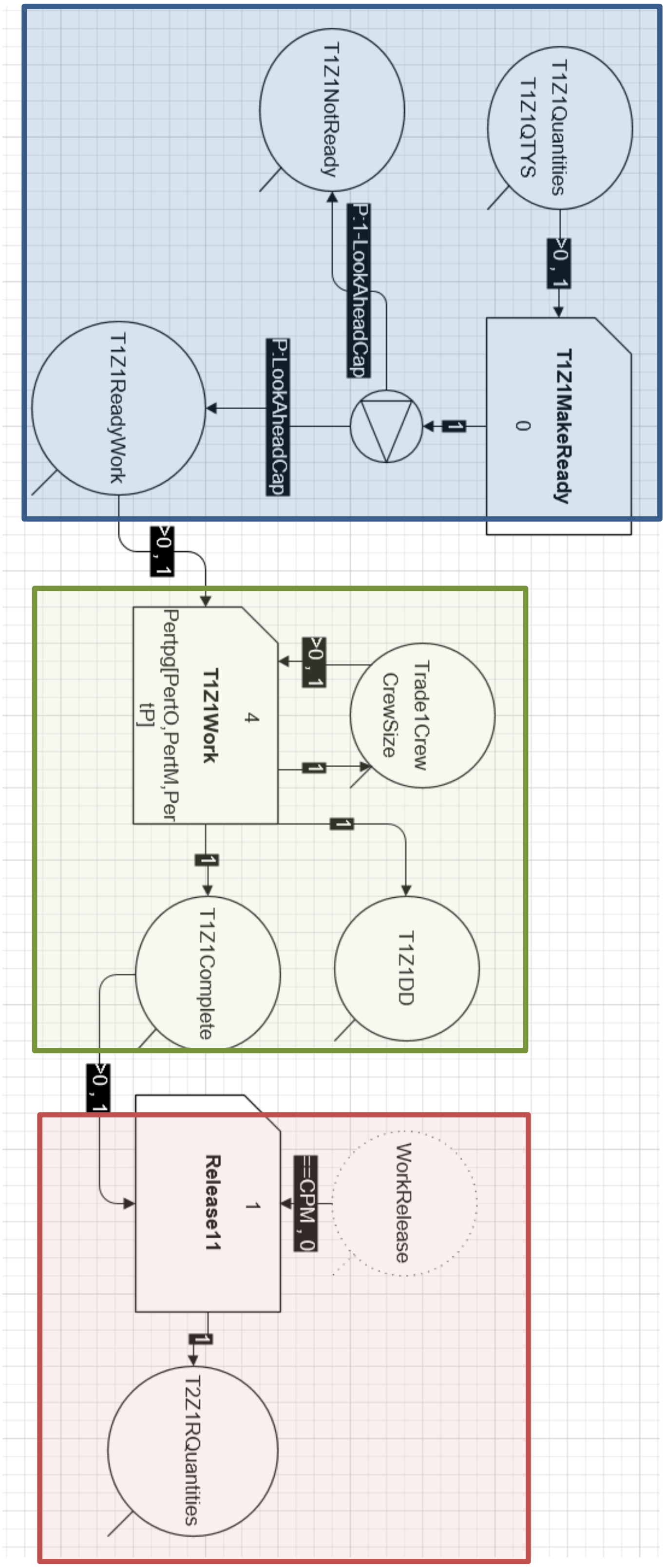


Figure 8-2 – Model for Trade 1 in Zone 1. (1. Screen (blue), 2. Work (green), 3. Release (red))

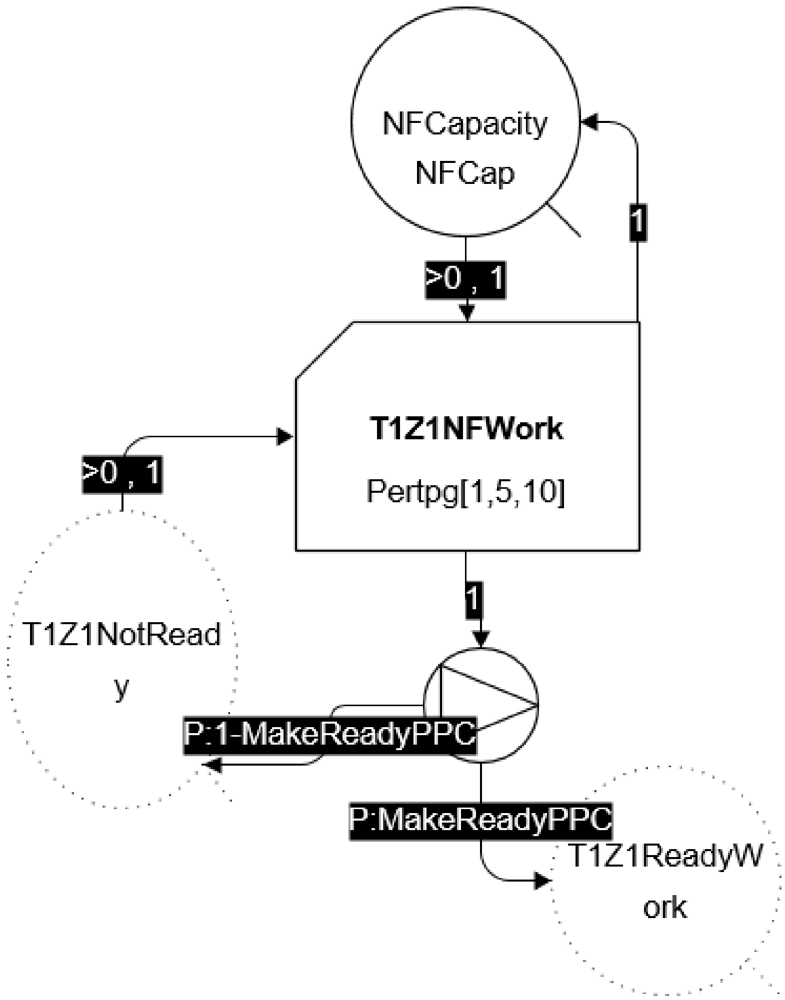


Figure 8-3 – Non-field work process for Trade 1 Zone 1

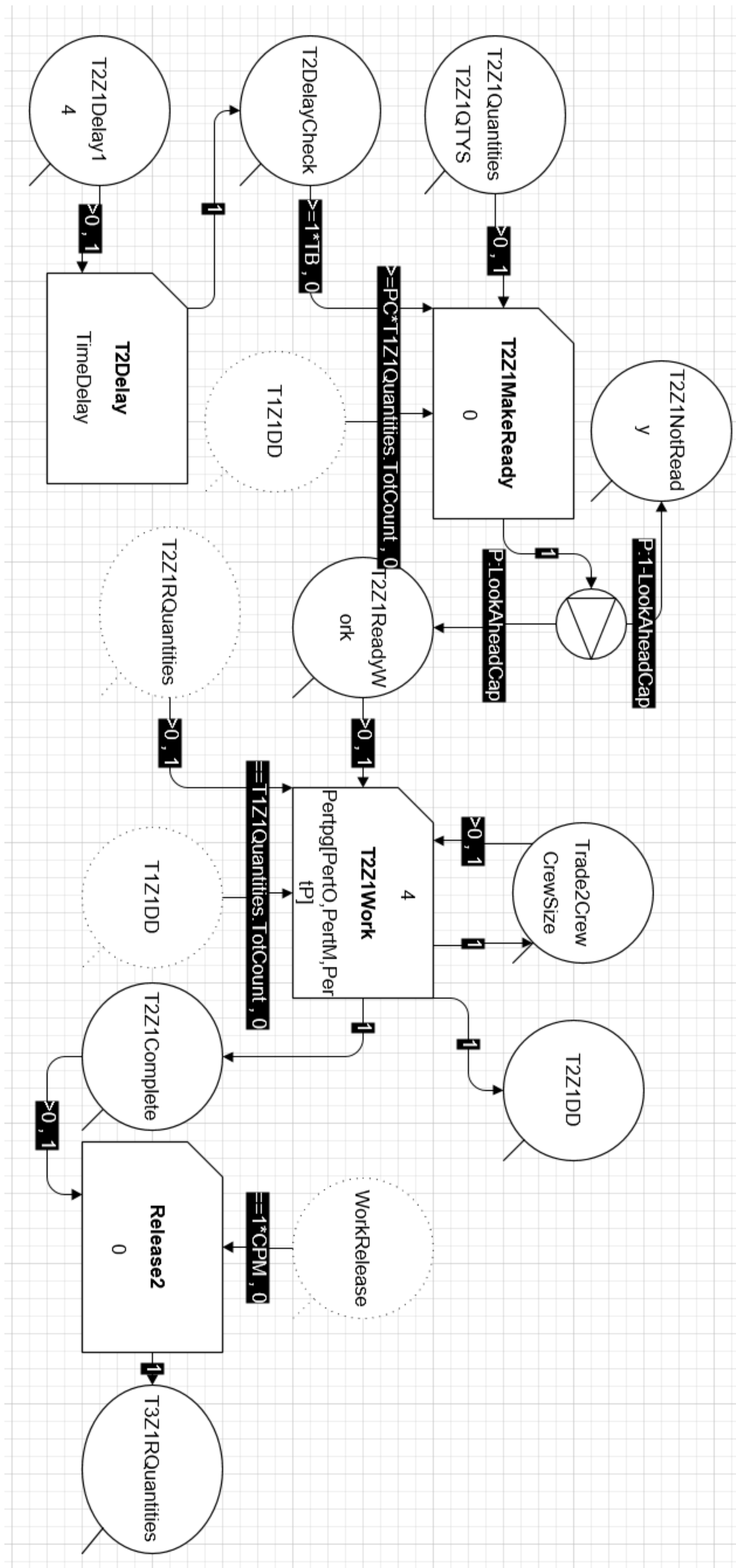


Figure 8-4 – Example of succeeding trades (Trade 2) after the preceding trade (Trade 1)

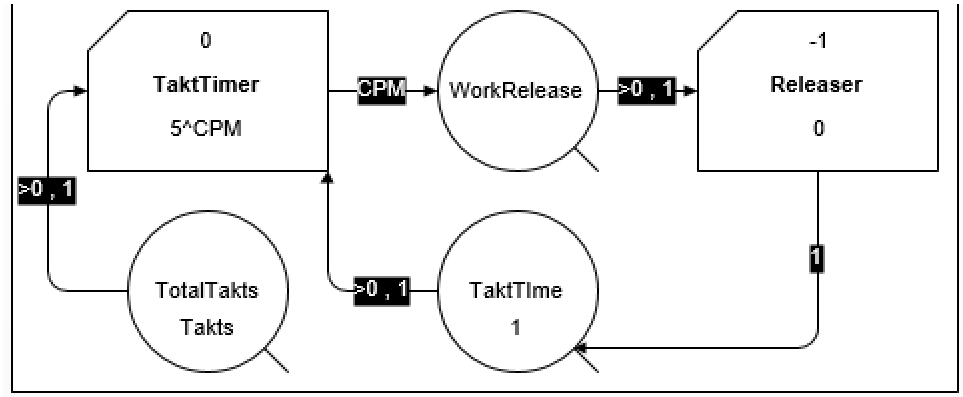


Figure 8-5 – Takt timer pacing process

Figure 8-6 provides an overview for the model, with arrows showing the flow of work. Detailed figures for every trade and zone are shown in the appendices. The trades are organized into rows; the zones are organized by columns of the work process. Each of the boxes labeled "Trade i Zone j" is one instance of Figure 8-4 for the designated zone and trade. When a trade completes work in one zone, it moves to the next zone and releases the next trade to start work in the zone it just left. This handoff is represented by the arrows in the figure. There are 16 different Make Ready activities (Figure 8-3), one for each zone and trade in the bottom left of the model.

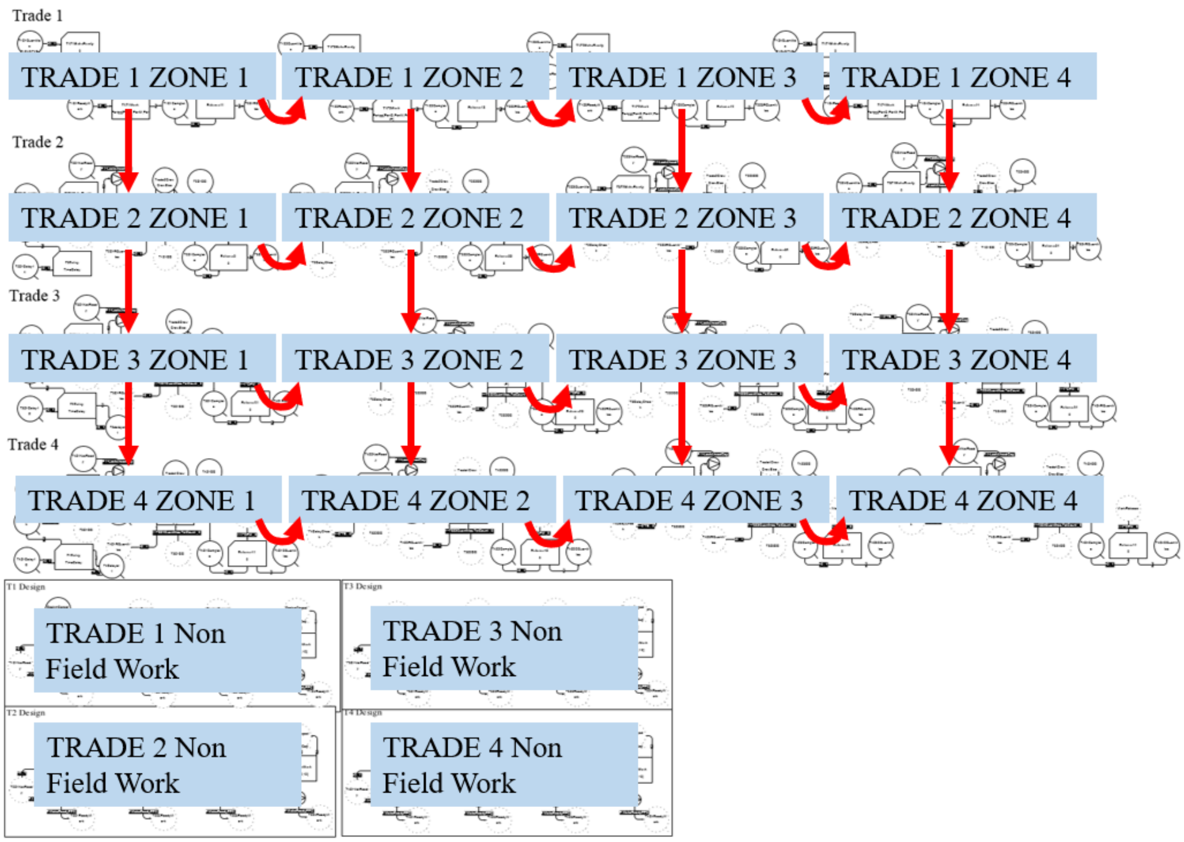


Figure 8-6 – Overview of the model (detailed view of every single trade in every single zone in appendix)

8.4 Experiment – Comparison of Takt Time Planning, CPM Schedule, and Time Buffering

Table 8-2 provides the variables that change for the comparison between a schedule using Takt time (TTP), time buffers (TB), and a Critical Path Method (CPM) schedule. In the CPM schedule, the first area for each activity will start as soon as possible (i.e., the TB variable is 0). The "CPM" variable is a binary variable used to turn on the Takt time pacing process (Figure 8-5) in the model, and is only used in the Takt time planning case. Table 8-3 provides the general variables that do not change between the different methods. The production duration was set to a PertPG distribution such that a crew of five could meet a five-day Takt time with 99.59% certainty. PertPG is used because it is a revised formula of the PERT distribution that produces a more accurate distribution to sample than if the actual distribution is unknown (Perry and Greig, 1975). All three scenarios use this production duration, but the crew size is higher in the Takt time planning case to use the crew as a buffer for some of the variation. For a sensitivity analysis, the production values were varied +/- 10%, and the LookaheadCap varied from 100%-70% in decrements of 10%.

Variable	TTP	TB	CPM
Crew Size	5	4	4
Time Delay	5	5-20 (increments of 5)	0
CPM	1	0	0
TB	1	1	0

Table 8-2 – Variables for initial comparison

Variable	Value	Unit
PC	80%	
MakeReadyPPC	100%	
LookaheadCap	100%	
Crew Costs	$200	per person
Quantities / Zone	25	Man-days
# of simulations	500	
NonFieldCap	15	
Total # of Takts	250	
Production Durations (per person)	PertPG(0.6, 0.8,1.1)	

Table 8-3 – General model variables for all experiments

8.5 Results

8.5.1 Comparison Between Work Structuring Methods

Figure 8-7 and Table 8-4 reflect the completion times for the different work structuring methods, given the setup described in the experiment section. The completion time is when the last activity finishes for the last trade. The Takt time planning scenario was the fastest, and contained the least amount of variation in time. Using a small time buffer (five days) between the starts of each trade was no different than the CPM schedule, presumably because the network relationships dictated when the activities could begin. With larger time buffers, however, the variation in completion time did decrease, because there was naturally less of a chance that required work would not be complete before the next trade began. Indeed, time buffering helps mitigate the impact of variation from preceding trades; however, too large a time buffer ends up costing more time without any further benefit to individual trade costs.

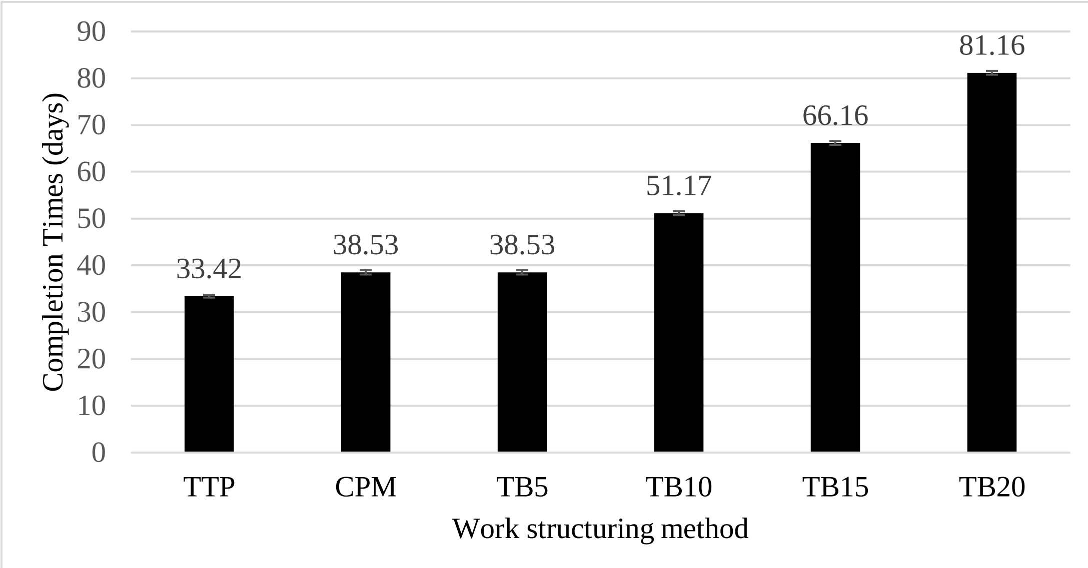


Figure 8-7 – Comparison between work methods on completion times

	Completion Time (days)	Standard Deviation
TTP	33.42	0.302114
CPM	38.53	0.486927
TB5	38.53	0.485251
TB10	51.17	0.413278
TB15	66.16	0.412901
TB20	81.16	0.409572

Table 8-4 – Completion times and standard deviations of work methods

Related to the previous figure are the total labor costs for each work structuring method. For many reasons, the Takt time planning work structuring method appears to have the highest costs. Costs for each trade are based on the crew size and how much time each individual trade crew needed to complete the work. The time buffer cases had the lowest costs and lowest variation on the costs (at the cost of a longer overall duration, as shown in Figure 8-8). While the labor costs may be higher in the simulation, if a project's indirect costs are factored in, the longer completion times may result in a more expensive solution. In this experiment, if the daily indirect costs are $454/day (or ~14% of the total crew costs per day if there are four crews working eight-hour days at $100 an hour) or greater, the Takt time planning case is clearly the cheapest and fastest. The formula for the break-even point is shown below as Equation 1.

$$Indirect\ Cost\ breakeven\ point = \frac{Difference\ in\ Total\ Labor\ Cost}{Difference\ in\ Completion\ Time} \qquad Equation\ 1$$

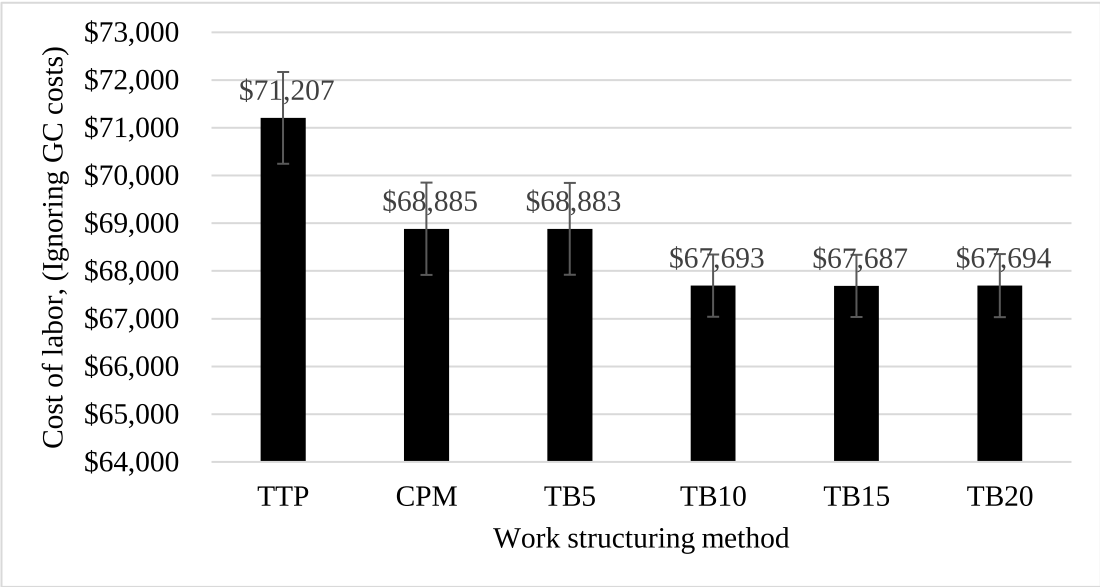


Figure 8-8 – Labor costs of work methods, ignoring general conditions, overhead, material, etc.

8.5.2 Sensitivity Analysis

The model could be inaccurate in a few areas, and sensitivity analysis helps to identify how robust the findings are, even if those inaccuracies were true. The production rate of the crews could be incorrect. How fast crews complete an activity is an important consideration for any type of work structuring method, so it is critical to understand how the different work structuring methods are affected by an error in the production rate. The PertPG formula constructs a beta distribution from estimates for the optimistic, pessimistic, and mode for the production durations for each crew member during each activity. Two additional cases were tested: (1) a slower case (~10% slower) with PertPG values of (Optimistic =0.65, Mode = 0.88, Pessimistic = 1.21), and (2) a faster case (~10% faster) with PertPG values of (Optimistic =0.55, Mode = 0.72, Pessimistic = 1.0). As shown in Figure 8-9 and Figure 8-10, the trends and conclusions are consistent across the different production scenarios.

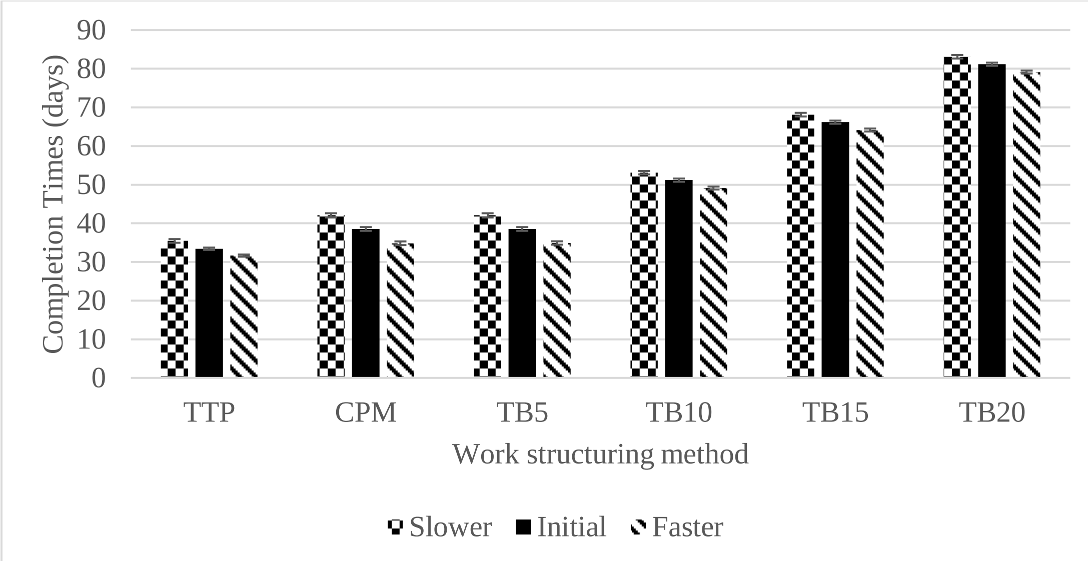


Figure 8-9 – Completion times in various production scenarios

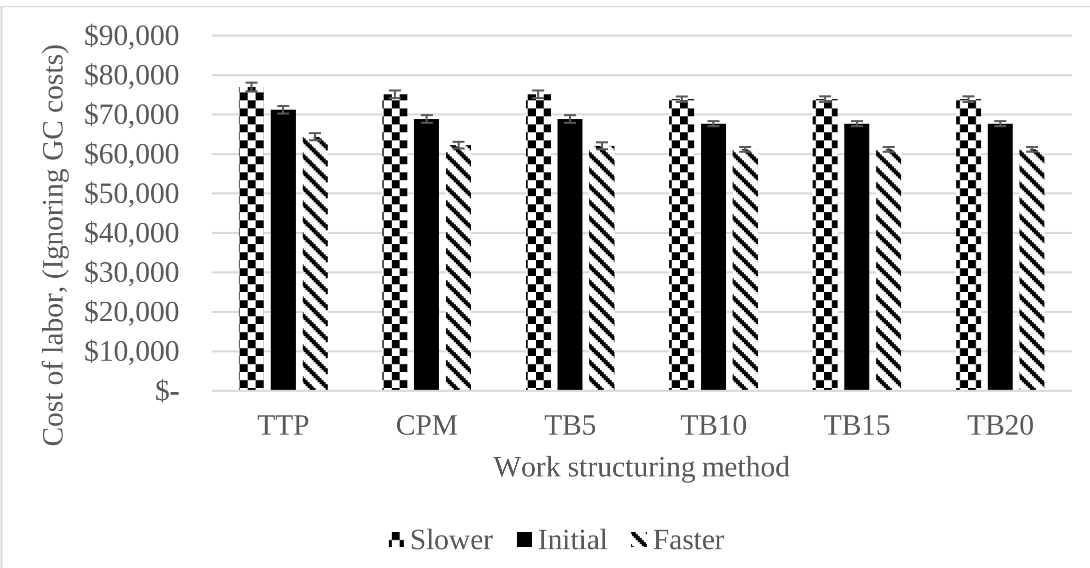


Figure 8-10 – Labor costs of alternatives for different work methods, ignoring general conditions, overhead, material, etc.

The Lookahead capability is a source where the model could be incorrect, and the sensitivity analysis shows that it does impact the results. The results are in Figure 8-11 and Figure 8-12. The work structuring methods with work scheduled closely together were impacted the most when the Lookahead capability decreased and Takt time planning was most financially impacted. Intuitively, this makes sense. In situations with low Lookahead capability (i.e., when problems appear the week work starts), using time buffers will absorb the problem (in cost and time), and capacity buffers will not. The same cost/time trade-off revealed in the initial simulation still exists, but the decision of which work structuring method to choose is sensitive to a team's capability to find and resolve problems before production is impacted.

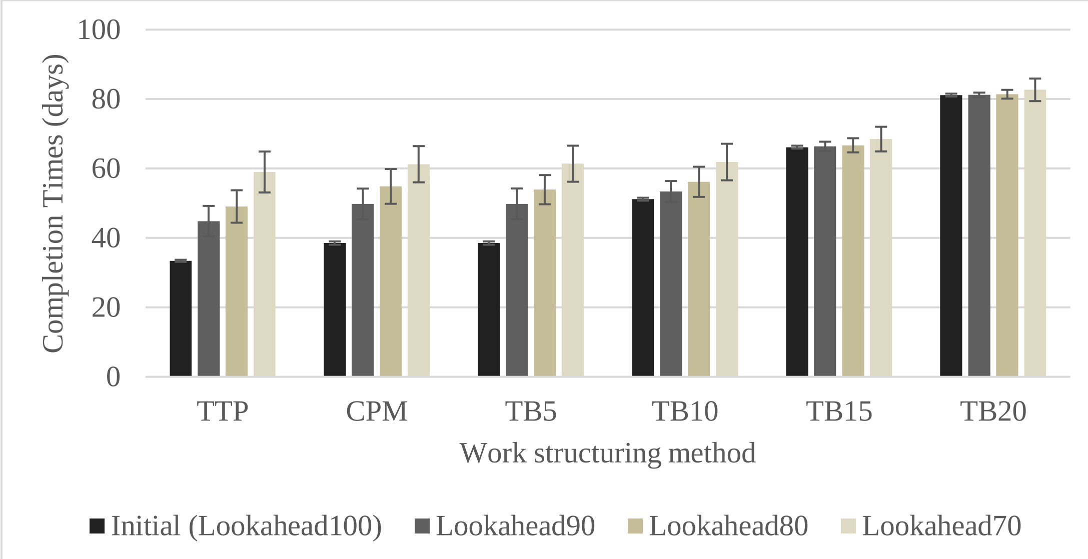


Figure 8-11– Completion times in varying Lookahead conditions

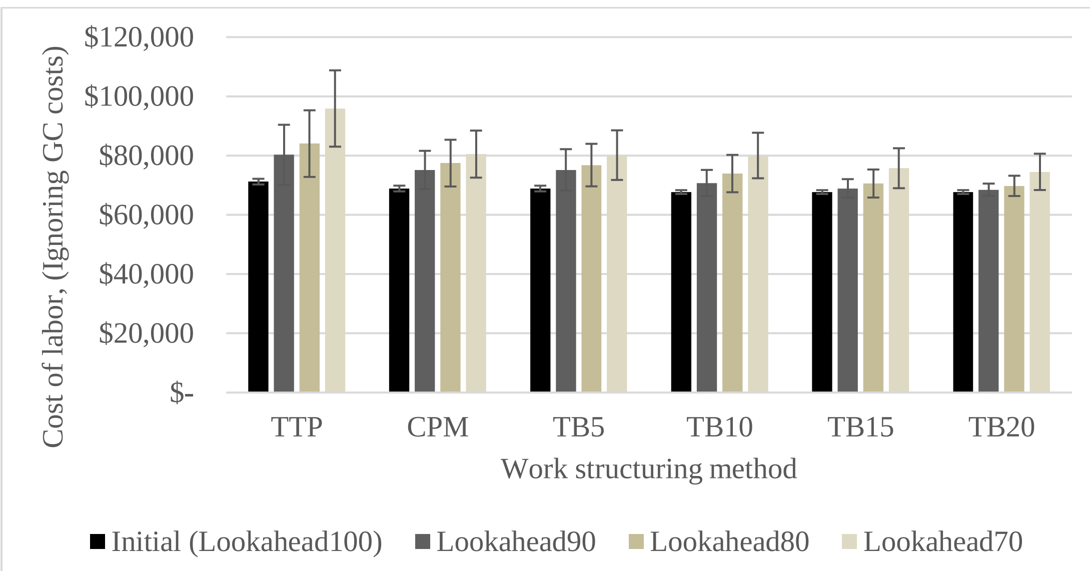


Figure 8-12 – Labor costs with varying Lookahead conditions

8.6 Discussion

Overall, this simulation is an attempt to model different work structuring methods used in interior construction. Simulating work structuring methods in different conditions is a substantial dissertation topic of its own. The inspiration to use time buffers came from how time buffers were prescribed by Seppanen in Frandson et al. (2015), and resembles the LBMS method. This simulation is also limited as it does not simulate the control methods prescribed; however, it does begin to compare the benefit and limits to using different types of buffers. A decision made in work structuring is where to place buffers and what type of buffer to use; thus, a model simulating the effects of those choices is valuable.

The results from the simulation are intuitive. In the initial case where all the variation is generated from production, the additional crew member serves as a capacity buffer, and Takt time planning succeeds as the fastest method with the least variation. However, in a simulated environment with variation that may not be buffered with additional production capacity, using time buffers is favorable. Variation that cannot be absorbed with additional production capacity would occur in non-field activities where the team cannot use the additional production capacity to maintain the schedule (e.g., the required material did not show up on site and the work is impossible to install). The simulation also showed that in no case was it preferable to use the CPM schedule. In theory, there is one case: when every early start occurs, and there are no misses in handoffs between trade activities.

The simulation assumes that each work structuring method uses the same production durations, zones, Lookahead capability, and activity sequences. Obtaining that information is partially dependent upon the process the team uses to acquire that information; consequently, this assumption does not hold up in practice, since different work structuring methods produce different results for all of those factors. If the same assumptions for durations, zone, Lookahead capability, and activity sequence are not used for the different work structuring methods then the results become trivial and self-fulfilling (i.e., the method with faster durations, with smaller zones, and less variation is superior). In addition, the ability to look ahead may differ among methods, depending on the simplicity of the schedule. For example, in the case of the CPM schedule allowing for early starts, the time frame for looking at future work may be smaller than in the other two cases; thus, it may be more difficult to catch and resolve problems.

The simulation assumes that the problems that arise are IID (independent and identically distributed). In practice, problems may be dependent (i.e., problems create more problems or relate to multiple issues), and more problems may appear, depending on the time on the project. The day of the week will likely matter, (i.e., more problems appear on a Monday or Tuesday morning than a Friday afternoon), and the time in the project also will matter (i.e., more problems appear during component layout in the first area than during installation in the last area). That said, the simulation effectively shows that if a team does not have the capacity (due to a lack of capacity or excessive demand) to solve these problems quickly during construction, the bottleneck will move from the field to the office where production cannot buffer with more capacity. In addition, time buffers help to decrease the potential problems that may occur simultaneously.

The cost used in the model is an approximation, but provides a good indication of the trade-offs between cost and time. However, it may be possible to maintain faster, more reliable speeds or production without using any additional crew capacity. Estimates for value-added time on construction sites are typically low (~25-50% per Oglesby et al., 1989), so there is ample room for improvement for teams to go faster, without incurring any additional cost. Finally, a project team could use this current model with their crew cost and general conditions data to estimate their team specific trade-offs.

The simulation was not externally validated by the case studies. However, the environments of the case studies were the inspiration for the simulation itself. When reflecting on the case studies, one element that appeared critical to the success of the plan was the dynamics between the capacity of the team to make work ready and the demand to make work ready. The simulation confirmed some observations on the case studies, namely Case Study 2, where the capacity to make work ready appeared to be a bottleneck on the system. In this circumstance, Takt time planning appeared ineffective (and time buffers may have been cheaper to use) because upstream Make Ready process could not meet the customer demand from the owner (the 10/20 due date) and the related Takt time.

There are several opportunities to expand the simulation. One opportunity would be to simulate the dynamics of starting work in a zone before the previous trade was 100% complete (at the cost of some production penalty) in the zone. This would facilitate the study of how incomplete handoffs impact work flow, and given the same parameters in this experiment, would likely penalize CPM with early starts more than the other two work structuring methods. Another opportunity would be to vary the number of zones, as the variation for each trade's costs increase with the trade number in the sequence. The simulation could also assess how different work structuring methods perform when no work begins before an initially planned start (often the case for certain types of construction work). Workable backlog could also be added to the simulation to directly account for how much time is spent, and how much time could be spent on workable backlog, given the different work structuring methods. The simulation could be altered to better understand how the crews are impacted by the different work structuring methods (i.e., how often they are idle, their production rates under different methods, etc.).

8.7 CONCLUSION

This model helps to answer the guiding research questions by identifying and quantifying the barriers to designing continuous flow. Flow on site is improved by using Takt time planning and capacity buffers, but it requires that all parts of the production system are aligned. Where there is no alignment between field and non-field capacities, a time buffer will be the only effective buffer. A notable finding from the simulation was that there was not any circumstance where the CPM schedule was the preferred work method. A workable backlog, though not modelled here, will potentially help to improve a crew's productivity if they become starved for work. In practice, it will not help the scope of work that is halted to finish faster, and will not help the schedule unless it keeps crews on site. In summary, this simulation demonstrated how flow on a construction site occurs when the field and the upstream activities to make the field work ready are moving at the same rate through the same zones.

CHAPTER 9 PROPOSED FRAMEWORK FOR TAKT TIME PLANNING

9.1 INTRODUCTION

This chapter provides a framework for Takt time planning in construction. It begins by defining the concept of work density, follows with project preconditions that provide the setting for implementation, and ends with a method for implementing Takt time planning. The concept of work density, the preconditions, and the method are all results from the case studies, for the case studies had different characteristics and different methods were tested. The preconditions were chosen because they appear to be what gives Takt time planning the best chance of succeeding, but are not necessary.

9.2 WORK DENSITY

Work density is the spatial distribution of installation time required to complete work in an area, and is a new concept related to Takt time planning. Work density is a function of the work contents (defined by the design and specifications), work methods, and crew size used to complete the work. The work density may be considered for a single trade or collection of trades in a specific zone or area. The work methods and work contents help to define the installation tasks required on site. When a task may be started and completed depends on a logical construction sequence (i.e., there are logical predecessor and successor relationships between tasks). Activities are a combination of tasks performed by a trade.

The concept of work density helps to define how Takt time planning aims to achieve flow on site. Flow on site is achieved by designing according to the time required to complete work (repetitive and non-repetitive) in each zone, rather than by quantities of work obtained from a quantity take-off. This is an important distinction, because a quantity take-off is simply a calculation of the types of components that are within the measured boundaries (the entire project, floor, zone, etc.). Thus, an ideal Takt time plan uses work density to evenly divide a space into zones, with equal amounts of installation time for each activity.

The work contents impact work density, and thus, the building design (see Figure 9-1). Consider two scenarios of work density for installing duct for the HVAC system. Scenario 1 has one shaft (the bold-bordered square with 10 crew hours of work), Scenario 2 has two shafts designed into the space (the bold-bordered squares with six crew hours of work each). Both scenarios contain the same amount of work in the space, but with different distributions. Assume the space needed to be split into two zones. If the split is by top and bottom half, then the top half has 20 more hours of work than the bottom half in Scenario 1, and eight more hours of work in Scenario 2. If the split is between the left and right half, then the left half has 28 more hours of work in Scenario 1, and the left half has eight more hours in Scenario 2. In either circumstance, having two shafts from which to build out results in a lower variation of installation times for duct work.

		2					
		5		3		3	
1	5	5	7	5	5	5	
1	5	**10**	7			3	3
1	5	5	5			3	
	3					3	3
	3	3	3	3	3	3	
		3		3		3	

Scenario 1 - One Shaft

Area	**Time** (crew hours)
Total	130
Top half	75
Bottom half	55
Left half	79
Right half	51

		2					
		3		3		3	
1	3	3	5	5	5	5	
1	3	**6**	5			5	3
1	3	3	3			6	
	3				3	**6**	3
	3	5	5	5	5	6	
		3		3		3	

Scenario 2 - Two shafts

Area	**Time** (crew hours)
Total	130
Top half	61
Bottom half	69
Left half	61
Right half	69

Figure 9-1 – Example of how design impacts work density (bolded cells represent shaft locations; numbers represent amount of work for duct install in the location in crew hours)

9.3 Preconditions for Takt Time Planning

9.3.1 Team Buy-in

Approval from each team member is critical to implementing Takt time planning, because if people do not want to adopt a method, it will not go well. Getting team buy-in may be possible by educating people on Takt time planning and building trust with the different team members. One way to accomplish both is to engage the team in playing the "Parade of trades" game. Playing the game is not necessary, but it is an opportunity for team members to get to know each other while learning how variation in work flow impacts throughput, and starves team members in a single-line production system that is analogous to how construction activities move through a space (Tommelein et al., 1999).

When a team starts a project, they should know that they will be using Takt time planning and be financially compensated for participating in Takt time planning meetings. This means that the decision to use Takt time planning occurs well in advance of the start of construction. This should not come as a surprise to the team during the project. For one reason, it may be perceived as a solution to an immediate scheduling problem and a lack of faith in the team to solve it. If that is the case, it could potentially affect the team's buy-in to using Takt time planning. If possible, the contract should also contain a section requiring that all team members meet weekly with the project team on site, via their foremen so the team members can budget accordingly.

9.3.2 COMMERCIAL TERMS

Team members should be incentivized to improve the total project cost and duration. This helps to create an alignment of interests between all members, and mitigates the risk of everyone individually optimizing to their own local concerns. This is important to Takt time planning, because the space is divided into zones and everyone moves at the same pace (i.e., production rate through the zones). Doing so may slow down some trades, speed others up, and sometimes require trades to share zones. The purpose of pacing the work and moving through a common set of zones in the same sequence is to avoid having trades fight for space or move around in an uncoordinated manner.

The integrated form of agreement (IFOA) contract is one contracting method that aligns the risks and rewards of individual members to the project success. If using an IFOA is not possible on the project, the contract should still provide incentives for different team members to meet collective goals.

9.3.3 ENGAGED OWNER

The owner's representative should be an active participant during weekly work planning meetings, and help to hold team members accountable on the project. Owner's representatives have a lot of power on projects, and their participation in the planning demonstrates support for the process. In addition, this provides an opportunity (if one does not already exist) for the project team to engage in a dialogue with the owner's representative about the owner's values on the project, and how their decisions affect delivery of the project.

9.3.4 MILESTONES

Milestones help to define the Takt time for construction phases. A milestone is a point in time on the Master Schedule that defines the end or beginning of a phase or contractually required event. Milestones for a project should be known, but there should be some flexibility in the intermediate milestones before the end date for the project team to adjust. While Takt time relates to the customer demand rate, it is also important to understand what is possible. If the planning meetings reveal that milestones are infeasible, it is better to reset them with the new assumptions rather than hold a project team to dates created with assumptions the team knows are incorrect.

9.3.5 PROJECT STAFFING FOR TAKT TIME PLANNING

The general contractor needs individuals responsible for maintaining the Takt time plan. Depending on the size of the project, one or more people will be necessary. The individuals could be project engineers, project managers, superintendents, or other leaders, but the important element is that someone is on site every day, supporting the Takt time planning effort. An engineer should be on site making sure that the plan is up to date, visual, and displayed in the field to communicate the plan accurately to the entire project. The visual plan is not necessary, but it helps to make it more transparent to everyone on site. The superintendent should guide the team to follow the production plan and not manage work based on a different plan. The trade contractors need foremen who understand their scope of work and are on site to help with planning.

In addition to the project team designating responsible parties for the Takt time plan, the general contractor should also have one (or more) of their staff maintaining the Last Planner System implementation on the project.

9.3.6 Building Information Modelling

Any new construction project should use a BIM model to coordinate design and provide the team with accurate information around which to build and plan. A BIM model helps the team in production planning by illustrating which activity sequences are possible. Projects that do not have a coordinated model or use BIM at all should be the exception, and have a justified commercial reason for not doing so (e.g., it may be cheaper to coordinate work in the field than developing a detailed model with the current team, see Case Study 3). If certain scopes are not modelled, a project engineer or project manager from the general contractor should track this decision to understand how the non-modelled scopes affected the project.

9.3.7 Member Experience with the Last Planner System

All companies working on the scopes of work planned to Takt times should have previous experience using the Last Planner System, and be familiar with how planning and control relate in the Last Planner System.

9.3.8 When to Plan for Takt Time in the Last Planner System

With respect to the Last Planner System, Takt time planning should begin before Reverse Phase Schedule, because it provides a first attempt at how the project can be divided into batches of work the trade partners can pull plan to during the Reverse Phase Schedule meeting. Selection of a Takt time and the zones to be controlled to begins as a gut feel based on several guidelines. The zones and Takt time must be big enough for the trades to work through productively, yet small enough to control to rapidly at a daily or shorter interval. The zones of work must also allow trades to complete work and flow in a logical sequence. This level of detailed planning also serves as a check against the initial assumptions used in the Master Schedule. The commitments made in the Master Schedule for each milestone set the demand rate for the project, so it is critical that the proposed Takt time for each phase of work sets a pace that meets this upper boundary of work.

Takt time planning also fits in at the later levels of the Last Planner System. Takt time sets in advance the locations that need to be made ready, and can help to provide a clear look ahead into future work for each trade. The Takt time also helps team members create quality assignments during commitment meetings. As outlined in 2.4, quality assignments meet four criteria: definition, size, sequence, and soundness (Ballard et al., 2007). Takt time plans begin to indicate the size, sequence, and scope for assignments to be committed. The Last Planner still needs to identify the soundness of each assignment: does the team have the prerequisite work done, do they have the material on hand, is the design complete, etc.? Last, because space where each trade works is clearly delineated activity by activity, it becomes clear to all whether or not work is progressing as planned.

9.4 METHOD

9.4.1 STEP 1 – DATA COLLECTION

Developing a Takt time plan requires collecting production data from each trade individually, and the team as a whole prior to starting construction. A Master Schedule may have been established, but before any production planning, data gathering begins with a production team meeting. This meeting should consist of trades (foreman and project manager) involved in the work and the general contractor (the project engineers, superintendent and project manager) to discuss the product of Takt time planning. The team must set their expected outcomes from Takt time planning (e.g., a chosen Takt time, with the same trade sequence throughout every zone and balanced work zones). The outcome may be specific (e.g., a one-week Takt time through 5-10,000 ft^2 zones for all inwall MEP rough-in work) and based on previous experience with similar work, or more general if the work and production team are new to using Takt time (e.g., create a plan where all activities move through the same zones, in the same sequence, at the same pace that will meet the Master Schedule requirements). The outcomes are up for the team to agree upon. It must also reflect the time the team will have to complete the work and milestones in between (e.g., specified in the contract including the Master Schedule). After establishing outcomes, the general contractor should schedule individual meetings with the trade.

The data to gather in individual meetings with each trade is specific to them, their work, and the project context. The objective of the meeting is to understand how the trade prefers and needs to perform the work in order to understand how the team can deliver the scope of work.

Gathering the data may also reveal work the team prefers to leave out of the Takt time plan. This may be appropriate if any area has a higher relative work density for a specific trade (e.g., electrical rooms for the electrical scope), or if an area has a high work density for everyone with respect to the surrounding space (e.g., operating rooms on the same floor as patient rooms). The trade contractor representatives should come to the meeting with a set of floorplans so they can mark them up and communicate the details of their work to the other meeting participants. The following is a list of questions to ask the trade contractors.

- How do you want to safely move through the project space, and what alternatives are available?
- What are your material and manpower constraints, or work method alternatives and their related costs/time impacts?
- What work needs to be performed before you start work?
- What is your internal work sequence (e.g., electricians want to set trapezes, run conduit, and then pull wire)?
- Can your work sequences be split, or can the work be performed in a later phase (e.g., does the electrician have to pull wire immediately after the conduit is run)?
- What work may be considered as workable backlog?
- What information would help you with your decision making?

Trade contractors may color-up the set of floorplans they brought in order to show their desired workflows, what can be completed, when, and with what assumptions. This helps to identify their work density, set of tasks, potential combinations of activities, and logical sequencing of the work. In order to understand the set of feasible options for a trade, the trade contractors must discuss alternatives to allow a set-based approach in developing the phase schedule, even though some options may not be optimal from their perspective. A set-based approach designs different alternatives in parallel, and removes alternatives only when they are no longer feasible (Parrish et al., 2008). The approach is a countermeasure to the negative iteration that point-based design may create when detailed, but incorrect information passes to downstream participants. Thus, in a set-based approach with scheduling, the scheduler begins with the various options from each trade to understand the feasible set of scheduling options that will work for the team.

The individuals representing the trade contractor in the conversation must be able to provide this level of detail and commit to doing the work in the way they describe it. The benefit to planning early with these details is that people develop deep understanding of their production capabilities and the resulting team's production plan from all the collected information. These conversations also provide an opportunity to understand the information the trade contractor would like to know.

It is important to ask about the assumptions and confidence in these durations and work methods. This is also an opportunity to understand how the trade contractor perceives and manages variation in the durations due to production-related issues. For example, assume the trade contractor proposes a set of zones by splitting the floorplan up into quadrants (Figure 9-2). There may be slightly more or less work in some of the zones (e.g., one zone may have 20 light fixtures to install, versus 16 light fixtures in all other zones), so they are confident they can meet the duration in certain zones. In these circumstances, it is important to explore how a capacity buffer may be used to make all the durations reliable.

To illustrate this point, assume that the left graph in Figure 9-3 represents the cumulative probability that a five-person crew will complete all light fixtures in any of the zones, and the right graph represents the same probability with an additional crew member. If we wanted a high reliability to complete each zone within six days, the additional crew member is preferable. However, if we needed to complete each zone within 10 days, the five-person crew would be preferred because it provides the same theoretical probability for lower cost.

16 fixtures	16 fixtures
16 fixtures	20 fixtures

Figure 9-2 – Sample floor plan, split into quadrants detailing how many light fixtures are in each zone

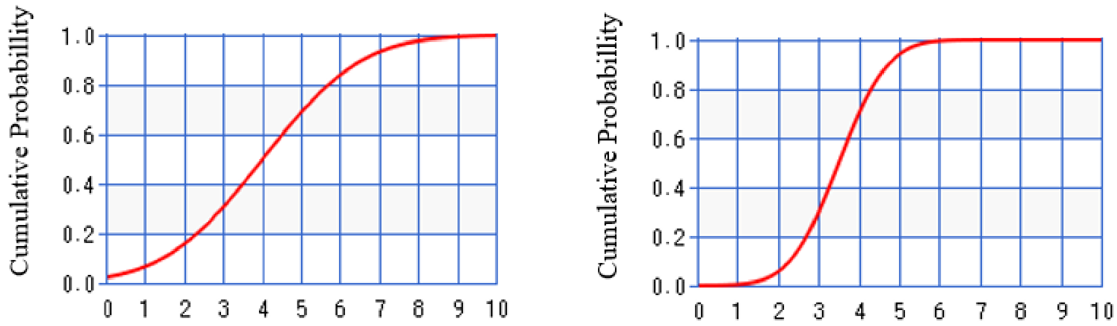


Figure 9-3 – Conceptual Cumulative probability functions of completion times through zones for one activity (Left: 5-person crew; Right: 6-person crew)

It is not usually possible to obtain any statistical data from contractors accurately depicting how long it will take to complete work. Regardless, by talking through these concepts with the trade contractor, it may be possible to reduce some variation in durations across zones with a capacity buffer. The trade contractor representative may have already included this buffer in their provided durations, but it is impossible to know if they did and to what magnitude if the question is never raised.

It is important to understand what the foreman is confident they can reliably produce so a Takt time can be set by the team that the foreman will own. If a foreman does not take ownership of the commitment, they may not care if the commitment is missed. The duration may be a target that would be "nice to hit," but not mandatory. Furthermore, if the foremen perceive the Takt time as important but not necessary, a similar loss aversion phenomenon seen in golf may occur, where people try harder to meet the "standard" (par), but do not try as hard when they perceive that they are exceeding the standard (making a birdie putt) (Pope and Schweitzer, 2011).

Separate from Takt time planning, there is value to project teams in understanding this information early. An early understanding of how trade contractors need to perform their work and the constraints they have helps to validate assumptions in current plans and facilitates execution in the future.

9.4.2 STEP 2 – ZONE AND TAKT TIME DEFINITION

Zone and Takt time definition relate to each other because the duration required to complete an activity (i.e., a scope of work in a zone) depends on what needs to be built and where. Independent of the zones, the team also needs to agree on what phases of work, including the first and last activities in each phase, will be scheduled with a Takt time. The team can start this discussion in the first meeting when identifying outcomes from the Takt time planning meetings, but now is the time to revisit the outcomes.

Zones are the areas each activity will complete in a Takt time, and are constant for all activities controlled to a Takt time in a construction phase. The team defines zones via an improvement process, starting from zones: (1) already established in previous work phase; (2) created using the data gathered in a holistic manner (i.e., all the trades are considered when creating the zones); or (3) designed to best satisfy and then improve the work of one trade because it is evident from data that they will be the “bottleneck” trade. The bottleneck trade is defined here as the trade with the longest durations through the zones. The defined zones are the starting points for iteration. Starting with zones from a previous work phase may or may not work for the current phase because the flow of work (direction, rate, sequence, etc.) may be completely different phase to phase, and a new set of zones may be a better option.

Creating the zones in a holistic manner begins with the data provided in meetings with the trade contractors. Each trade contractor provides a set of options via the color-ups. By overlaying the color-ups or laying them all out next to each other, it is possible to understand what types of zone configurations will likely work for the team as a whole.

In combination with the zones, the team can revisit the durations and identify how long it will take to move through the proposed zones. The Takt time is set by the maximum time it takes for a trade to move through any of the zones. The durations should have some capacity buffer (i.e., resource underloading) to account for variation in production, and execute the work in a reliable amount of time. At this time, the team can also identify other options for providing additional buffers in capacity. For example, can the team work on Saturdays or overtime during the week? For a large project, this appears to be a feasible option to help buffer work releases. Is there enough work considered workable backlog crews can work on, but also switch over to Takt time planned work if needed (i.e., are there available crews elsewhere on site that can help speed up Takt time planned work if it falls behind?)?

Structuring work in smaller batches has schedule benefits. Figure 9-4 reveals the benefits of moving through a 12-floor building with varying amounts of zones. For example, assume the durations are 12 weeks per floor for every activity, with evenly split zones. Thus, it takes a single activity 144 weeks to fully complete work through 12 floors. The different curves on the chart represent a different number of activities in a sequence. The handoff between activities is a “finish-to-start” relationship; when one activity finishes, the area is handed off to the next activity to start.

The figure shows how moving from one zone per floor to smaller batches produces significant schedule benefits (e.g., in the case of a four-activity sequence, moving to four zones from one zone improves the duration 56%). However, when defining zones and Takt time, the figure shows several trends a production team must consider. First, there are diminishing returns, all activity sequences approach the horizontal asymptote at 12 weeks due to how much work is on the floor for every activity. Second, the schedule benefit to increasing the number of zones improves with the number of activities in a sequence. Third, increasing the number of zones increases the number of concurrent activities and the number of handoffs that need to be managed. Related to the third, the fourth trend is that the Takt time, the rate the handoffs are made, decreases with the increase of zones.

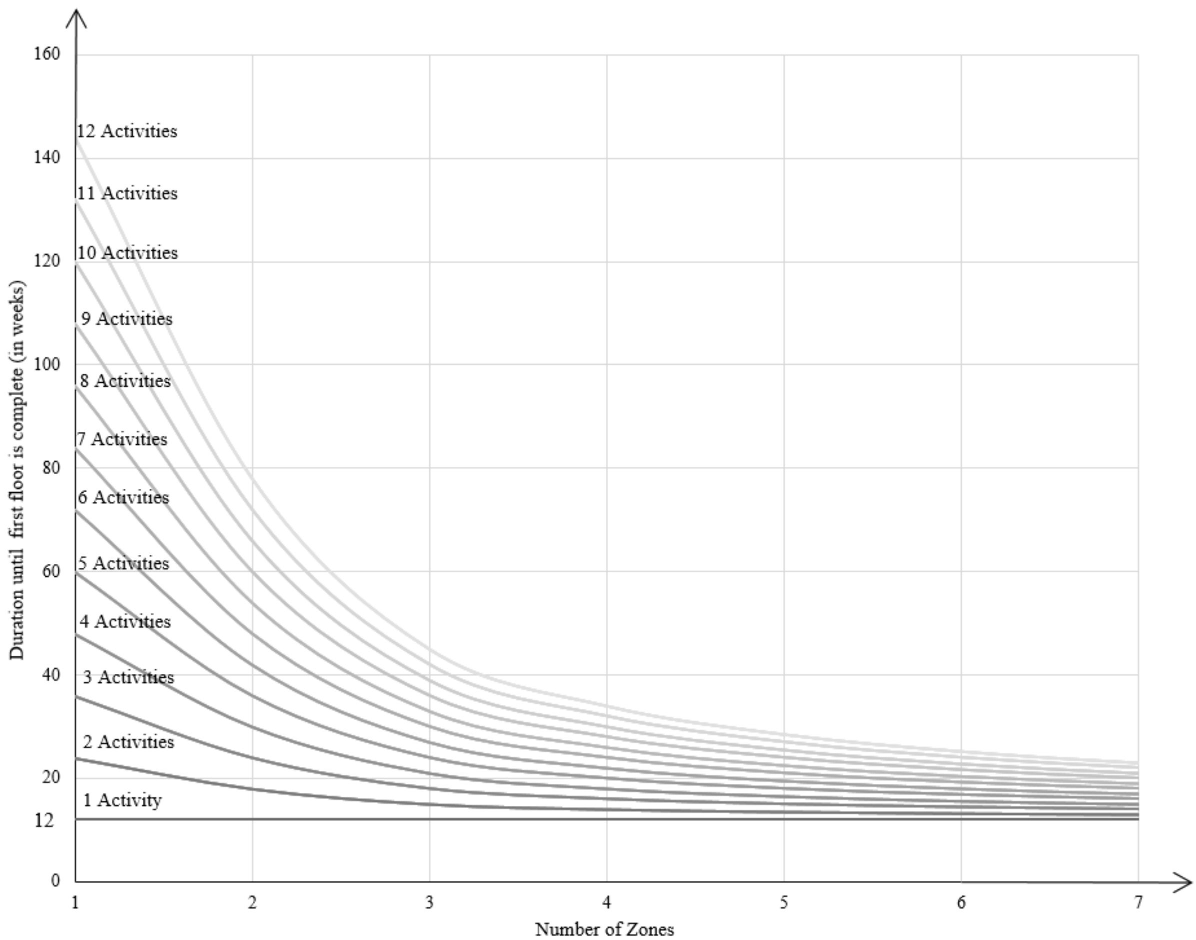


Figure 9-4 – Effects of the number of zones on the overall activity sequence duration with different numbers of activities in the sequence

9.4.3 Step 3 – Trade and Zone Sequence Identification

Given a set of zones, the activity sequences are obtained from each trade individually, then combined in a Reverse Phase Planning meeting to honor sequential dependencies while reviewing the construction documents or building information model with the team. When identifying the activity sequence (that does not need to be a linear sequence,) it is important to document the specific requirements each trade has to release zones from one trade to the next. Ideally, the team should move through the space in the same order to maintain flow. It is possible for all trades to flow through zones in different sequences and maintain continuous work, but the resulting plan is not as simple. If moving through a non-linear sequence (i.e., trades move through the zones in different sequences), it is important to ensure that the resulting schedule does not create discontinuous work for the trades. Maintaining continuous work is important in the linear sequence as well, but if every activity is moving at the same rate in the same zone sequence, it will naturally occur.

Based on all of the data, the team needs to decide to move through the space in the same zone sequence (i.e., a linear sequence), or move through in orders preferential to the different trade activities. The configuration of zones, design, work methods, and Takt time impact whether is feasible to move through zones in the same order.

9.4.4 STEP 4 – BALANCING THE PLAN

Balancing the plan occurs in a rough-to-fine fashion. With defined zones, it is now possible for the team to refine the activity durations for each trade. It would be rare if all trade activity durations were perfectly balanced through every zone from the beginning.

The production team has several methods to balance workflow and design the production system. The following is a list of methods, but there is no priority implied regarding how to apply them.

- The team can iterate upon the zones. If the zones are consistently uneven in durations across the trades, the team can redefine them.

- The project team can change the actual design if it is early in the project (before detailed design is complete) to improve production. It may be possible to reduce work density variation by moving components in more dense areas to less dense areas, or simply making the work area less dense. Some examples of this are using two smaller duct shafts versus one large duct shaft (e.g., Figure 9-1), changing the locations of home-run boxes and electrical rooms, or using an alternative detail for how two components come together. Some of these options may only be advantageous if they are understood early enough in the project (i.e., it would cost more total time and money to change the design, than if the team produced the schedule off the current design).

- Some trades may have to leave out certain work and perform it "off Takt" in a sequence outside of the Takt time plan.

- Revisit the work methods. Perhaps a trade can individually, or jointly with other trades prefabricate more work and reduce their field installation times, enabling a lower Takt time. Prefabrication may not yield an immediate cost savings for the trade, but it may help the project overall, because a faster Takt time may produce overall cost savings for the project.

- Revisit the trade scope (this is easier to do if the contract structure allows scope to move between trades).

- `Restructure the activity sequence to balance the work. Some activities can go faster if they go in earlier (e.g., full height walls can likely be framed faster if there is no overhead MEP installed). Ultimately, these sequence decisions come down to what work truly needs to be done at a particular time to be constructible, versus what work would be more convenient or faster for a particular trade. Having these sorts of conversations requires trust and transparency, showing that the changes will benefit the project as a whole. If the team shares and divides the total profit, the owner incentivizes these solutions.

- The activity sequence could also change by splitting the tasks making up a single activity into multiple activities, lengthening the total duration for a scope of work, but allowing a faster Takt time for the phase. This often shortens the overall schedule because a reduction in Takt time scales across the number of zones through which the trades move.

Figure 9-5 illustrates how the three-day Takt time is faster, even though it has more activities in the sequence. As an example, consider four activities moving through four areas with a four-day Takt time (Alternative 1) to five activities moving through four zones at a three-day Takt time (Alternative 2). In Alternative 1, activity 4 required four days and has two tasks associated with it: installing electrical conduit and pulling electrical wire through it. In Alternative 2, activity 4 is split into two, three-day activities (4.1 and 4.2) and each task (install conduit and pull wire) is now a separate activity.

							Finished
Days	4	8	12	16	20	24	28
Zone 1	1	2	3	4			
Zone 2		1	2	3	4		
Zone 3			1	2	3	4	
Zone 4				1	2	3	4

							Finished
Days	3	6	9	12	15	18	21	24
Zone 1	1	2	3	4.1	4.2			
Zone 2		1	2	3	4.1	4.2		
Zone 3			1	2	3	4.1	4.2	
Zone 4				1	2	3	4.1	4.2

Figure 9-5 – Example of how more activities in a sequence can be faster than fewer activities at a slower Takt time (Top: Alternative 1, Bottom: Alternative 2)

Ideally, the team notices that an activity sequence will not work through a zone early in planning (in steps 1-3). However, if it does occur while balancing the plan, a sequence deemed infeasible can sometimes be made feasible by "flipping" the sequence between two or more activities through zones to maintain the overall production schedule. Flipping between two trades occurs if they switch the order through two zones.

This solution does not always work, because it may create discontinuous workflow. Figure 9-6 depicts the workflow problem. When two activities are flipped (known as "a flip") through two zones, the flip creates times when a trade is not working on an activity for a Takt time, and times when the same trade needs to work on two activities simultaneously. If there is workable backlog, the trades have additional crews to use for the Takt times when two crews are required, or the flipped trades are not the bottleneck trade, this type of solution may be feasible. A flip also can be feasible if the involved trades have other projects they can move crews to and from. However, flipping may not be feasible if the project is small and there is not a lot of labor, workable backlog, or close projects to allow manpower to fluctuate and remain productive.

Days	4	8	12	16	20	24	28
Zone 1	1	2	3	4			
Zone 2		1	3	2	4		
Zone 3			1	3	2	4	
Zone 4				1	2	3	4

Figure 9-6 – Example of flipping an activity sequence performed by separate trades (Trades 2 and 3) through Zones 2 and 3

9.4.5 Step 5 – Production Schedule Finalization

Finalizing the production schedule requires validation. Every trade needs to check that their sequences are feasible, and that they can perform the assigned work in each zone in the given Takt time.

9.4.6 Step 6 – Plan Execution

With a finalized plan, the team can now execute the work. The team should use the Last Planner System or an equivalent system for production control for several reasons. The team needs a Lookahead process screening tasks for readiness. In order to learn from mistakes, Last Planners should commit to activities in the Commitment Planning meeting. To help track progress, an engineer should log activities in a spreadsheet or planning software. To make the plan visual and transparent, the general contractor should post the plan to which the team committed in the field on a board. Every day, the Last Planners should meet for a daily huddle with the superintendent and project engineer to maintain transparent communication, common understanding of the plan, and rapidly correct problems. In order to have an effective daily huddle, every Last Planner should be able to answer three questions: 1) What did I get done; 2) What do I commit to doing tomorrow; and 3) What new challenges in the field emerged today?

Takt time activities are complete in a timely manner when they do not impede the work of the succeeding activity. Ideally, the activities always complete 100% of the work in the zone. As an example, if plumbing inwall rough-in succeeds framing, the framing needs to be completed in the zone such that the plumbing inwall rough-in will not be affected by their handoff of the zone if it is not 100%. If the framing activity is not on track to finish 100% of the work, the framer needs to utilize the capacity buffer they have, work overtime, reallocate additional manpower, or make an agreement with the plumber to complete the area by temporarily sharing the zone with them. Regardless of the decision, the framer should not negatively impact the plumber's work in the zone.

9.4.7 Step 7 – Updating the Plan

If the plan changes and creates a circumstance in which the Takt time exceeds the required demand rate for the project, the team needs to iterate through the first six steps again. Before moving through the six steps, the team should first assess the current situation, starting with identifying why the plan has changed so the team avoids the change in the future. Second, the scheduler should calculate the new maximum Takt time required to deliver the scope of work that meets the project requirements, given the same activities and zones as the current plan. Third, the team should gather new data and understand which assumptions have changed since the Takt time planning began so the new plan is feasible. The updated data and improved understanding of what is possible may bring to light new opportunities to improve the overall schedule.

9.5 METHOD OUTCOMES

1) Balanced, detailed production schedule
2) Shared (early) understanding of how all trade contractors need to perform their work
3) Shared understanding of the plan
4) Understanding of work that is and isn't planned to a Takt time, and how much capacity buffer everyone is using
5) Agreement on the plan

CHAPTER 10 DISCUSSION

10.1 Introduction

This chapter begins by outlining the differences between the three case studies, then uses findings from the case studies and simulation to answer the research questions, followed with a general discussion on topics not covered by the specific questions.

10.2 Cross-Case Comparison

Table 3-1 summarizes the different characteristics of the Takt time planning case studies. The succeeding sections provide further analysis of their differences, and begin to explain how those differences may have affected the implementation of Takt time planning and the delivery of the project. Each case study had the following unique characteristics:

- Case Study 1 designated an engineer to help with the Takt time planning implementation, and this seemed effective for communicating and maintaining the Takt time plan daily
- Case Study 1 had the highest team buy-in and the engaged owner throughout the entire project appeared to be a cause for it
- Case Study 2 was the only case study that attempted to execute to a strict Takt time plan with the same durations, trade sequence, and zone sequence
- Case Study 2 was the only project that was OSPHD 1 compliant (Case Study 1 was OSHPD 3), and the researcher observed that this requirement made a much higher demand to make work ready than the other two case studies
- Case Study 3 did not use an IFOA and opted for a GMP contract with hard bid subcontractors; keeping an early engagement with the subcontractors may have captured some of the benefits to using an IFOA with respect to Takt time planning
- Case Study 3 project members had not used the Last Planner System before, and it is possible that this affected the project members' comfort with planning work to smaller zones
- Case Study 3 did not have a coordinated BIM model or use visuals in the field to control the Takt time work; however, the project was not negatively affected, due to the combination of effective field coordination and the less strict inspection requirements

10.3 Questions

10.3.1 What does Takt time planning in construction look like?

The dissertation aimed to answer the question of what Takt time planning in construction looks like. The process described in Chapter 8 was the result of iteration on the Takt time planning method throughout the case studies. The resulting plan and execution of it, based on the case studies, depends on the project characteristics.

For interior construction, Takt time planning involves workers moving around the work. In all case studies, the work was not repetitive, and the project teams found different ways to implement Takt time planning and move through the space. This was a key finding of the research. How specific trade crews on each project move through the space may be the same or different. In Case Study 1, the different trade crews moved through the space at a set Takt time, but in different zone sequences. The team used visuals to communicate the plan daily to everyone. In Case Study 2, the different trade tasks were structured into activities with the same Takt time and zone sequence. In contrast to the other case studies, the Case Study 2 phases depended on when the pre-cast structure was released for the interior build out, rather than using phases dependent upon groups of similar work (i.e., overhead MEP rough-in, inwall MEP rough-in, etc.). In Case Study 3, the trade crews moved at approximately the same rate, but the assumption that they needed the space to themselves was relaxed, as the trade crews were small with respect to the size of the zones. Case studies 2 and 3 also used different scenarios to communicate how different configurations of zones, crews, work days, and Takt times would affect the overall schedule. In all cases, the production team aimed for a feasible schedule, speed, and reliability.

10.3.1.1 **What are the characteristics of flow in construction?**

In construction, flow occurs when the trade crews, material, and information continuously move at the same rate. The information (design, specifications, directives, etc.) need to flow through the virtual space and match up with the physical flow. Flow for one trade crew is a state in which they can move uninterrupted from zone to zone continuously. In a Takt time setting, this may mean that a trade crew finishes early in a zone and needs to work on workable backlog, or use the time for continuous improvement (training, testing new methods, planning, etc.). For multiple trade crews, flow may not be apparent if the work moves in different sequences for every trade. However, flow may still exist in that circumstance if all of the crews are working continuously and uninterrupted. As shown in Case Study 3, the crews may also flow together if it is feasible and productive for them.

10.3.1.2 **When should construction aim for flow?**

For interior construction involving multiple trades moving through the same space, aiming for flow even if the work is not repetitive (i.e., the same work in every zone) appears to be a beneficial goal for which teams should strive and is a highlight of the research. There are examples where it would not make sense to aim for flow, however. One example comes from Case Study 1. In Case Study 1, interior wall framing was not paced to a Takt time with the overhead MEP rough-in phase activities, or the inwall MEP rough-in phase activities. The rationale for not doing so was because the activity could complete the entire area so much faster than the other work around it. In cases where there are drastic differences in crew production rates, it may make more sense for the project not to limit the pace of the work. In addition, the case studies had examples of activities (e.g., setting thermostats or registers) that did not necessarily need to flow or follow the planned sequence because the work was not labor intensive, did not require space for itself, or was a short activity that a subcontractor would perform briefly, then leave the project. In more general cases, flow may not be a goal if it is too costly to achieve, or if the only feasible way to align several activities would result in a schedule that did not meet the owner's requirements.

More broadly, the case studies provide evidence that Takt time planning is a good candidate for multiple types of construction. High-rise residential projects, large stadiums, large hospital projects, malls, hotels, schools, industrial construction, and road construction all appear to be good candidates for Takt time planning because of the potential to break the work into phases and pace activities through zones with similar amounts of work. However, Takt time may not be appropriate for projects where labor flow is not a constraint. An example of such a project is the construction of an offshore oil platform, where the main goal is to deliver the project as soon as possible to begin oil production. Understanding where people are working is important for safety reasons, but there is no strong need for balancing the work through areas. In addition, there are no set beats that crews need to work to during operations.

10.3.1.3 **Under what conditions is there a benefit to scheduling work while underloading?**

Based on the case studies, scheduling work while underloading requires a few conditions to be beneficial. Regardless of the contract structure, the team members must be willing to collaborate and deliver the project by making some compromises with each other. One example is Case Study 1, where the drywall contractor was not paced to the Takt time, but had access to the entire space to install all of the walls. Installing at the same Takt time as the plumber and electrician may have been more convenient for the plumber and electrician in the inwall MEP rough-in phase. This is because they would not have to leave the space temporarily to let the framer install the walls; however, allowing the framing work to complete in this manner was much more efficient for the project. In the same phase, the plumber had to make the compromise of slowing down to the four-day Takt time to work at the same pace as the electrician.

The project team must also spend time to plan and balance the work between the different trades. In all three case studies, the production teams found ways to balance their work through work structuring and designing zones that produced an amenable schedule for all participants. In order to realize the production schedule, the field work needs to be constraint free, and the entire project team needs to ensure that the schedule remains feasible. Case studies 1 and 3 were examples of how the Takt time plan remained on track because the project team removed constraints effectively and the field could execute to plan. Case Study 2 was an example where capacity buffers may not have been utilized well because the work was not constraint free.

While underloading is critical to Takt time planning in theory and has demonstrated benefits in the simulation, understanding how much crews buffer with capacity is still an unknown and a future research topic. On no case study was the researcher able to accurately quantify how much of a capacity buffer was planned by the foremen.

10.3.1.4 **How can using Takt time planning as a work structuring method improve decision making for project execution?**

As a work structuring method, Takt time planning can improve decision making for project execution in several ways. Takt time planning attempts to optimize at the project level by creating a reliable, balanced plan. The teams from Case Studies 2 and 3 attempted this when the researcher calculated multiple scenarios for the team to understand the effects of their decisions. Early engagement helped both teams from case studies 1 and 2 identify long lead items and improve understanding of how the different team members needed to work on the project. The early meetings also forced the trade contractors to think critically about how they could perform their work and their work flows. In Case Study 3, this also resulted in the superintendent thinking about how he'd like to split the work into phases and how the strategy for completing the finishes phase would be different from the previous phases (see 7.3.1 for how visuals were used to help communicate this idea).

In all case studies, the Takt time plans revealed problems that became critical to the schedule. These are problems that the team would likely face, regardless of how the work was structured. However, Takt time planning exchanges schedule flexibility (or lack of a detailed plan) with a rigid plan which demands that problems are solved immediately by the team. Schedule flexibility here refers to the multitude of feasible options to schedule a project.

10.3.2 WHAT BARRIERS EXIST TO DESIGNING CONTINUOUS WORKFLOW OF ACTIVITIES IN CONSTRUCTION?

Several barriers exist to designing continuous workflow of activities in construction, and the case studies provide some insight into countermeasures. The first barrier is social. The second barrier relates to variation in production. The third barrier relates to variation in work density inherent in the work. The fourth barrier to designing continuous flow relies on the ability of the team to follow the schedule.

The first barrier is social: teams need to feel ownership in their plan and buy into the Takt time planning process. The entire project team needs to attempt to follow the resulting production schedule from Takt time planning. Maintaining this schedule requires discipline from everyone. One strategy to help with buy-in is to get the team involved early in the project. In Case Studies 1 and 3, the researcher engaged with the team months before construction began, and before the team had a detailed schedule. Because no schedule was in place, they were able to create the schedule together and likely feel more ownership of the schedule. In Case Study 2, production research began before construction, and the milestones were already known but not on track, so they required adjustment from the team. Consequently, the general contractor introduced Takt time planning as a solution, but the team did not buy into it, and one may question how much the timing of the introduction was a key reason for the failure to achieve buy in.

One strategy for maintaining discipline is to display the plan daily and have someone (or many people) responsible for holding everyone accountable for maintaining it. In Case Study 1, two individuals held people accountable. The owner attended every weekly planning meeting with the team, encouraging their development and execution of the Takt time plan. Case Study 1 also had a dedicated project engineer who collected daily Takt time planning reports and maintained the visual production board on site. Engineers are critical because they help to create transparency, as everyone on site gets to see the plan, decentralizing control of it. These two team members were not present in Case Studies 2 and 3 at the weekly planning meetings, and those two projects did not follow the plan as closely as Case Study 1. Thus, project engineers and owners are critical to ensuring that the team follows the plan because they hold team members accountable from the top-down (owner) and bottom-up (project engineer).

Related to the social barrier to continuous flow is the practical ability to follow the plan. This relates to the knowledge of the project team, how constructible the project is (regarding design and specifications), how well the design and specifications are communicated to those performing the work, and the team's capacity to solve problems. Case Study 2 provided several examples when the team simply could not follow the plan. Shafts could not be framed because the pre-cast openings were too big. Rebar was spaced so closely that electrical boxes could not always be installed in the pre-cast walls as planned.

Variation in production between planned and actual completion times is another barrier for continuous flow, and has multiple sources. One source of the variation is that the crew members are changing (i.e., trades are moving their labor across multiple projects at any given time to meet the company's needs). The crew size may also vary from the plan due to external pressures. In addition, too many people on a crew will affect production variation due to congestion and management issues. The people on crews vary, and as each individual has different capabilities and skill sets, there will naturally be variation in the resulting work. Production variation also occurs when people do not work continuously and need to start and stop multiple times throughout the day. Mobilizations at the starts and ends of the day are inevitable, but how individuals need to move through the space daily will also create variation. The time of day, day of the week, and environmental conditions all affect the completion times.

Material handling and logistics also add to the variation in production. Case Study 1 was on the ground floor and trades could move material into the building from a front entrance. The conditions were not as convenient in Case Study 2. The material needed to roll around the building on dirt or wooden planks. The area also was not accessible with machines because the pre-cast work required external bracing around the perimeter of the building (which took up the remaining available space), and move onto the first floor or be lifted up to the second floor. Where the material is stored with respect to the work will also create variation in production. Case Study 3 also had access from the ground floor and moved material in and out of the front entrance. Flatbed trucks could unload material right in front, so material did not need to move far from the flatbed to where it needed to be stored on site.

Tool and equipment availability will also impact variation. In Case Studies 1 and 2, overhead work was performed in scissor lifts, whereas on Case Study 3, all overhead work was performed on ladders. Though the projects involved similar work contents, the methods impacted how quickly people could complete work in zones. One foreman said they estimate working about half has fast through a space if it is off a ladder versus a scissor lift.

Variation in work density is another barrier to continuous flow. Because the work is not uniformly distributed across the floor and does not have the same distributions for every trade, there is a lower boundary to how small zones can be before the variation results in infeasible schedules for everyone. Some variation exists because the building serves different functions and requires multiple systems to come together to form the functioning building. Naturally, there will be different building components in different areas of the building. However, all three case studies indicate that this was a source of variation that can be reduced in design.

During design, if a team considers the work methods and how the work is distributed across the space for everyone, it may be possible to design less work density variation into the building without changing its function. In order to explore this option, a team would need to design with a production plan in mind. Involving trade contractors early to communicate how different design decisions impact the work density variation between zones would help, but this would also require that the contractors make these calculations frequently in design.

This is not an exhaustive list, but it is quite clear that the field faces several sources of variation, many of which can be reduced and/or eliminated through planning. In other cases, the variation may be buffered with extra capacity. The simulation experiment in Chapter 7 helps to quantify these benefits. Though all work structuring methods had the same production variation, the Takt time planning scenario, with the use of capacity buffers, resulted in completion times with less variation than the other cases. In Case Studies 1 and 3, the capacity of the project team to make work ready was not a bottleneck to production, and thus, Takt time planning appeared to work well. The simulation confirms this relationship. While capacity buffers may help absorb some variation, there are circumstances where they are ineffective. The simulation and Case Study 2 reveal that a capacity buffer is not effective when a bottleneck exists upstream and work that must be made ready relies on non-field capacity. Thus, if a team is going to use Takt time planning, then it also needs to attain buy-in that the entire project team can meet the requirements of the resulting plan.

10.3.2.1 What types of variation may be absorbed with capacity?

This research identified different sources of variation. Buffering with capacity appears to be effective when the variation directly affects the time spent working on the activity in a zone. There are various sources of this type of variation.

- varying work density per zone
- environmental conditions (is it hot or cold)
- skills of the people performing the work
- familiarity with the work (understanding the scope of work, processes on site, and the plan)
- function and availability of equipment
- number of starts in the day
- material handling requirements
- variation in start time during the day and number of starts

Time buffers appear to be more effective in dealing with upstream activities involving activities like design and material procurement that would normally halt all construction if not completed. During construction, it may also be more effective to use time buffers in cases where work is not completing due to design conflicts and other constructability issues from previously installed work (i.e., the as-built condition requires additional information for construction to proceed).

These conclusions are somewhat intuitive. Nevertheless, if a project team desires reliable handoffs of work, then it is important for them to recognize their sources of variation in order to develop the correct countermeasure to reduce the variation and mitigate its effects.

10.3.2.2 How reliable are Takt time plans?

Percent plan complete metrics, overall project schedule data, and simulation help to answer this question. Table 10-1 displays the PPCs broken out by phase for the different projects. Because Case Study 2 and 3 had inwall and overhead work occurring simultaneously, the work planned to Takt times is combined into the respective phases. On Case Study 1 and 3, the PPC was higher in phases planned to Takt time planning compared to the phases that were not. More data is required for this finding to have statistical significance, however. Case Study 1 and 3 reliably completed on time. In the simulation, Takt time planning had a smaller variation in completion time and a comparable variation in labor cost with the CPM and five-day time buffer scenarios.

Project and Phase	PPC
Case Study 1 Phase1 – non TTP	78%
Case Study 1 Overhead MEP – TTP	95%
Case Study 1 Inwall MEP – TTP	85%
Case Study 2 - Pre TTP	63%
Case Study 2 – TTP	73%
Case Study 2 – Finishes – non TTP	63%
Case Study 3 Demo/Structural - non TTP	86%
Case Study 3 MEP Rough-in – TTP	75%
Case Study 3 Above Ceiling and Finishes – TTP for Above Ceiling work only	74%

Table 10-1 – PPC Summary Chart for different projects and phases

10.3.2.3 **What are the consequences of designing a production system around different zone sizes?**

The case studies helped to identify various consequences to designing production systems around different zone sizes. The zones are closely related to the Takt times, and are a fundamental element to using Takt time in a non-repetitive environment like healthcare construction. Larger zones will typically yield longer Takt times (i.e., 10,000 ft^2 zones will typically take longer than 1,000 ft^2 zones), but are also dependent on the phase of work (i.e., finishes work may move faster through a zone than inwall MEP installation). Longer Takt times provide an opportunity to correct the course within the Takt time, whereas a shorter Takt time may require additional time (in the form of a time buffer or use of overtime) to maintain the handoff. On Case Study 3, the five-day Takt time in Phase 1 performed differently than Phase 2 (with a one-day Takt time). In the case of the one-day Takt time, by the time the team knew they could not complete a Takt time sequence, it was already too late to resolve the problem before the next trade needed to work in the zone.

The size of zones will also affect the variation between zones and trades, and within trades. Due to the size of the zones, people may estimate higher durations because they are focused on a larger set of work, and may include more time to account for their own uncertainty. This may create more or less flexibility to perform workable backlog during execution. Zone sizes also appear to impact Lookahead, because they increase or decrease the focus on the specific work within a zone. On Case Study 1, the foremen needed to focus on small areas one at a time, and were able to identify small areas within the zones that did not fit the planned sequence. One explanation could be that because they focused on small zones rather than large ones, they were able to fully complete their work in the small zones because they placed a priority on completing the work in the zones, combined with understanding all the different work that needed to be performed in the zone.

10.3.3 What are the costs and benefits of using Takt time planning?

The case study results were positive overall, but the results were mixed. Case Study 1 finished on time and 12 days faster (on day 44) through the overhead MEP phase and eight days faster (on day 37) in the inwall MEP phase. On the contrary, Case Study 2 finished three months behind schedule and 10% over budget, but it is not clear how much extra labor was used as a capacity buffer on the project, if any, that is attributable to Takt time planning. Case Study 3 finished on time and only used 23% of the budgeted Saturday work. Case Studies 1 and 3 also finished under budget.

The additional cost to using Takt time planning on Case Studies 1 and 3 was the additional meeting with each individual trade contractor to review their work, and the kick off meeting to meet the team and play the Parade of Trades game. On Case Study 1, an engineer also helped post the daily plans (on a weekly basis) in the field and collect the daily reports. The additional cost on Case Study 2 was that each trade contractor met at a one-hour production meeting weekly throughout the duration of interior construction. Case Studies 1 and 3 did not require additional labor than budgeted to meet the schedule requirements. From the simulation, Takt time planning labor costs were higher than using a time buffer or a CPM schedule with early starts, but became more favorable for the project if daily project's indirect costs exceeded 14% of the labor costs. Overall, the benefits of using Takt time planning, engaging project participants to plan the work before construction begins and understand how they need to perform their work, appears to be worth the costs.

Referring back to the example in Figure 9-4, the general and trade contractors spend more effort managing the handoffs due to the increased number of network relationships and the increased frequency of handoffs (e.g., handoff a floor every 12 weeks, versus every three weeks/zone in the case of quadrants). In theory, there should be no difference between the scenarios because the production rate does not change, only the rate of measurement. In practice, there is a difference, and it will place more strain on the team to manage the work. This actually can help to keep a project on track due to a faster feedback loop, and it should outweigh the costs of increased effort. Therefore, it is important to map out the production management processes used on site, ensure that they scale well, and the project is staffed adequately with people in charge of managing the handoffs or simply maintaining the system can become a risk to delivering the project. In addition, there must be some trade-off between the total project cost benefits and the cost to manage the system, however none of the case study participants reported any change in their overhead costs due to using Takt time planning.

Last, the team must also acknowledge the risk involved in Takt time planning. If a team develops a Takt time plan where several crews moves at the same Takt time at the same sequence, they are all critical to one another in following the plan. Thus, if one cannot meet the requirements of the Takt time plan, they all need to collaborate and restructure the plan.

10.4 General Discussion

10.4.1 Buy-in is Critical

Obtaining buy-in from teams to use Takt time planning was critical for implementation, and it varied across the case studies. The person appearing most effective to get the team to follow the Takt time plan on a daily basis was the superintendent. If the superintendent did not value the plan at a daily level, it was not going to be followed as closely. In Case Study 2, team buy-in was lowest, and where the team was introduced to Takt time planning the latest. The late introduction appears to have caused low buy-in. Consequently, it was also the case with a one-day Takt time in the second phase of work. The Takt time was initially followed by the trades, but was halted when design issues prevented certain activities from starting. The issues were not communicated until the weekly work planning meeting, yet foremen could have shared the issues sooner if the team had been checking production daily. As such, failing to control at a daily level defeated one of the primary benefits (i.e., smaller handoffs translate to a faster schedule and faster feedback if the plan is on track or not) to using the Takt time plan with a one-day Takt time in the first place. In future Takt time planning implementations, the control frequency (the frequency at which the team checks that the plan is being followed), should be greater than Takt time. This can increase the likelihood of meeting the Takt time plan because it allows the team to identify and resolve issues during the given Takt time. Future implementations should also start Takt time planning with the team before construction begins.

The Case Study 1 team bought into the Takt time process a few weeks into the overhead MEP rough-in phase when they realized they really were going to get space to themselves to work productively and started offering additional ways they could improve the plan. The team found the board in the field helpful, and based on the data, worked towards the Takt time plan. It was a similar situation for the Case Study 3 team. The team followed the visual production plan placed in the field, but would also work ahead of the schedule if allowed. Unfortunately, Case Study 3 lacked a responsible individual to maintain the visual boards, so they were eventually abandoned and not updated after the first two weeks.

In general, the different trade partners were primarily concerned with their individual productivity. Future research should test how Takt time planning is implemented when team members have the field capacity bought out, or with a general contractor self-performing work, similar to how capacity may be bought in factories to transfer risk. Such an approach would theoretically eliminate or further mitigate trade partners' incentives to optimize locally and focus on global project needs. A good case for this test would be a project with lower risk of not making work ready in the Lookahead window.

10.4.2 Takt Time Planning Does Not Make a Bad Team Good

Takt time planning will not make up for poor design, Lookahead, or lack of quality control. On the contrary, it will highlight all of these flaws, due to following a zone sequence with standard handoffs of work. However, Takt time planning appears to make good teams better, due to the benefits of smaller batch sizes, standard batches of work, and a more predictable work environment. This relates back to Taiichi Ohno's writing on the waste of overproduction. Overproduction was his chief waste because it hid many problems in production systems. Takt time planning attempts to eliminate making do (at the cost of schedule flexibility/uncertainty in the plan details) and overproduction. The trade-off is that more problems will surface at a rate the team may not be to resolve adequately.

10.4.3 Interior Planning is Flexible

As a general observation, execution of interior construction in all the case studies was quite flexible, and Takt time planning made this flexibility clear. Each team member had many ways they could work that were either communicated initially in the meetings, or arose based on the project demands. Even then, the true sequence logic for each component going into the building was never as strict as the plan dictated, so the communicated work sequences were making an incorrect assumption at the component level. From the trade contractors' perspective, one purpose of their stated sequences was to minimize the number of required passes and the difficulty of each pass. The degree to which the work sequence assumption is correct is a function of the zone size. Assuming people review and understand the work, if a zone encompasses more components, it will be less likely for one sequence to catch all of the components. Regardless of the accuracy of the stated sequence, Takt time planning and the initial meetings provide an opportunity to communicate some flexibility with the team, enabling them to create better plans.

Though the Takt time plan was rigid, it helped to reveal some team members' flexibility. The one-day Takt time on Case Study 2 was not strictly followed, but because Takt time plan released work every day, it forced the team to find solutions and work arounds on a daily interval to production challenges. Trade contractors in general showed flexibility in their ability to provide manpower to the projects. Except in Case Study 3 where crew sizes were minimal (i.e., one person) in some phases, adjusting manpower to balance the speed at which the team moved through the building provided an effective way to help with balancing. As such, understanding the set of crew size options for each trade partner was critical.

Case Study 3 also revealed how large zones relax the constraint of keeping one trade in a zone at a time. The zone sizes may also result from the team's unfamiliarity with the Last Planner System and Takt time planning in general. Regardless, frequently, several trades worked in a zone, but in different areas within it. Thus, the work likely could have been scheduled with smaller zones if the team had been more receptive to the idea. In addition, during the initial planning process, the team did not have a clear idea of where they could start on the project. Takt time planning proceeded by outlining zones and target times to move through the space, independent of sequence. When uncertainty from the structural work cleared up, the team committed to a zone sequence.

10.4.4 Lookahead Process Observations

Implementing Takt time planning on the case studies revealed how the lack of a Lookahead process could impact the realization of the plan. The researcher observed that a Lookahead process needs to be prescriptive in what to look for, and when. Recent research found that most plan failures occur on components that show a conflict in the model, or were not modelled at all (Spitler et al., 2015). The problem, however, is knowing what to search for in the model in order to screen for activities accurately. Last, the Lookahead process must not seem overly pedantic to the team, or it will be challenging to get team buy-in. Regardless of the work structuring method used, or what a project team calls Lookahead, all teams need to perform Lookahead in order to complete projects successfully; this is critical to construction management.

10.4.5 Work Structuring: Zone Configurations, Pacing Work, and Scheduling

Activity concurrency typically increases as the number of zones increases. While eight zones may be all a project needs to assume most of the schedule benefits from smaller batch sizes (assuming the zones are broken down into equal parts by work density for each trade), what may begin to dominate production system design is that a team can opt to use different durations through zones for different activities with smaller zone sizes. If the scheduler relaxes the assumption that the zones are equal, or the production rates are different, the schedule becomes more varied and complex. It is possible to model these effects, or at least to quantify them in schedule alternatives or examples.

It is also assumed that if an activity requires 60 man-days to complete, spending the installation time is equal across different crew sizes. A crew of six for 10 days may not work at the same productivity rates as a crew of four for 15 days, or three for 20 days. Depending on the material logistics, it may be possible to schedule work of different trades in the same zone, because people are working in different areas within the zone. The "worker density" in this case could be modelled along with the plan as a resource-loaded schedule over the project's floorplans. Creating worker density schedules would also provide data for the production question of correct crew sizing for specific types of work.

If trades are working through a zone simultaneously, the zone could likely be divided into smaller zones under different project conditions. However, if the zone size remains a larger batch size than the minimum (i.e., the smallest size the team is willing to use) possible zone size, this may be an option to move through the space at a faster rate. Thus, the team could move through two 'half-size' zones for five days, or through one 'full-size' zone for 10 days, but with both trades working simultaneously. Since no handoff is made until the end of 10 days, tracking the production through the zone becomes a challenge of discerning between bad production variance that will prevent the hand off at the end of 10 days, and production variance that will be absorbed by the capacity buffer. The physical release of zones may be easier to manage in the half-size zone scenario, because the goal is measured more frequently and completing the smaller batch within the timeframe may be easier to gauge, as a foreman does not need to forecast as far. Consequently, if the alternative is not possible, tracking production through 10 days may be the most feasible option.

Project teams must be careful when permitting this type of scheduling, however, because it can quickly resemble tradition, of scheduling trades by floor with a few days of lag between them to "stay out of each other's way" without considering how the material and crews use the space. Simultaneous area scheduling while considering worker density is quite different, because it requires detailed planning with the team, rather than hoping that different crews can stay out of each other's way.

Every building component has network activity logic associated with it. When project teams schedule larger than the component level (which they always do for practical reasons), the team assumes they can install enough components to productively start and finish an activity related to the components. When teams begin to execute a plan, foremen are actually looking for releases of batches of components, regardless of the planned flow they assume will be productive for their crew to work on. Ideally, the two are the same, but it is easy for the release of batches to be different, because the true network activity logic may be different from the scheduled logic shown in the plan. Foremen can also create mixed batches containing components from different activities that are tracked informally and/or discretely to create productive sets of work for their crews. As such, balancing between releasing a productive number of components to individuals on a crew and following the plan precisely may be opposing goals. The countermeasure for this is to simply communicate when the goals oppose so the team can plan the work accordingly.

10.4.6 Incremental Levelling

One idea not tested in the case studies (because they were too small) was the idea of incremental levelling. Incremental levelling could be one means to achieve buy-in from a team by starting out slow, and improving upon the Takt time as the team becomes more familiar with the work. Something similar appeared to happen in Case Study 1 during the overhead MEP rough-in phase, where the team only realized that they could move faster through the space when they started the work. Another example possibly coming from necessity rather than buy-in occurred in Phase 2 of Case Study 2, when the team moved from a five-day to a one-day Takt time through smaller zones.

Whether a team takes advantage of incremental levelling or not, a Takt time plan should be structured so it is feasible from the beginning (i.e., the plan meets the owner's end date). Incremental levelling should be a means of achieving greater project savings from lower general conditions and improvements in productivity. If there are shared savings between the owner and the contractors, both parties benefit from schedule improvement, even if the owner does not need the building any earlier than their required date.

An alternative to incrementally levelling the Takt time is to incrementally level the crew size over time. Case Study 1 showed that less manpower than initially planned by the foremen was required to perform the work. Takt time planning may be a means to improve upon overmanning if project teams can quantify how to measure buffers in capacity.

10.4.7 Integrated Project Delivery and Takt time planning

Work structuring from a lean perspective requires downstream partners to be included upstream in the design phase. Integrated project delivery is a mechanism for providing an incentive for downstream subcontractors to be included in the design phase. The next step in production system design is to create common understanding around what needs to be built, and how it needs to be built. IFOAs were used on two of the three case studies. Case Study 3 was an example where it was not used, but the subcontractors were still engaged before construction, and their input helped to produce the schedule, and delivered the project successfully. This indicates that the IFOA may not be necessary, only beneficial to increasing incentives for the trades to optimize the project as a whole.

The commercial terms of an IPD agreement share the risk and rewards between project participants. However, an observation in all case studies (IPD and non-IPD) was that the burden of productivity and resource utilization was always placed on the trade contractor. While the commercial terms result in the team bearing the financial risk, the trade contractor still held the blame. This may or may not limit the set of feasible schedule alternatives during the initial planning and execution. The same resource utilization phenomenon occurs with non-field personnel, which we know from the simulation can create bottlenecks that cost a project time and money.

10.5 Limitations, Reliability, and Validity

There were several limitations in this research.

- Data collection due to time on site and current practice; this limited how much productivity and schedule data could be collected

- A risk in design science research is overgeneralizing the benefits of an artifact. Two of the three projects finished successfully, but it is still unclear how much that success (perhaps none) was a direct consequence of Takt time planning.
- Number of case studies is small and focus on one type of construction
- Bias towards companies involved in lean construction and the Last Planner System
- Project size (primarily due to time constraints)
- Projects are all located in California where construction methods and technology may be different than other areas internationally; however, this also makes the case studies more comparable between one another.

Case study research builds reliability when multiple sources of information converge on the same findings. In this research, three case studies used a method for Takt time planning to successfully produce production schedules. Internally, the case studies used multiple sources of evidence to form their individual findings. The case studies all occurred in California and focused on health care projects. While this may seem to lack generality, the focus of the research was on a method to develop continuous flow in interior MEP build out that relies on work density, which is based on installation hours. This is a general problem all building projects face during interior construction. Health care is a subset of building construction types, but they are quite complex and require strict building codes; thus, if a method works in a healthcare environment, it is safe to assume that it can transition to other building types. In fact, Case Study 3 in Danville had less strict requirements, which is more analogous to commercial construction, but was the fastest and most financially successful.

The case studies are a good basis for this research due to their completeness. This research aimed to develop and test Takt time planning in order to understand the benefits and challenges of flow in construction. That requires a high level of involvement with project teams from the beginning to the end of implementation. On all three case studies, the researcher worked with teams, from creating the Takt time plan, until the Takt time plan completed execution. All case studies used the method, improved upon it, and implemented it in different ways, depending on the team's preferences and capabilities. While Takt was not followed closely on Case Study 2, this provided keen observations into the social and practical problems of Takt time planning, which later inspired the simulation. Case Study 3 was another example of how the team disproved an assumption that crews need space to themselves, but still followed the plan overall and delivered the project successfully.

In addition to the case studies, simulation provided a controlled environment to test the assumptions and compare work structuring alternatives. Simulation allows for statistical validity due to the ability to run multiple independent samples. Thus, simulation provides a powerful complement to observations and findings from case study research.

CHAPTER 11 CONCLUSIONS

11.1 CONTRIBUTIONS TO KNOWLEDGE

The objective of this research was to develop and test a method for producing flow in non-repetitive settings, and to understand the barriers to continuous flow. Non-repetitive interior construction was the focus of the research due to the nature of the work; if the method works in this setting, it follows that it can work more generally in other repetitive or non-repetitive settings. Achieving this objective is an important contribution to theory because it enables lean concepts (e.g., Takt time, continuous work flow, level loading) to be used in practice, and increases the knowledge related to project production system design. The research also provided examples, methods, and barriers to using Takt in non-repetitive interior construction. Though lean construction theory has called for planned resource underloading and creating flow, neither of these necessarily occurs without a method to follow. The rationale for creating flow was that even though the components may vary throughout a building, it may still be possible to design zones with similar amounts of work (by work density) so multiple crews can complete their work and move through the zones at the same pace.

That supposition has been confirmed in the case studies, which have shown that it is possible to take seemingly non-repetitive work and design zones such that trade crews can move through the zones at the same pace. This is possible in part by involving the trade contractors early in the planning process, which is important in order to achieve their buy-in, plan the work, and include their input to create a better plan. One way to maintain reliability in repetitive and non-repetitive settings is to use a capacity buffer to absorb production variation.

This research also generated a model that improved understanding of the trade-offs between the three – time, capacity, and schedule – buffers used in construction scheduling. As discussed in Section 1.1, current practice typically opts to schedule with time buffers and an undefined capacity buffer. Exchange between buffers may produce system benefits, but a production system must meet other conditions for a project team to realize any benefits. Thus, there are circumstances where capacity buffers are preferable to time buffers (e.g., when there is sufficient capacity to solve problems and use the capacity), and vice versa (e.g., in conditions when a team cannot remove constraints fast enough).

While Takt time planning may help a team produce a schedule with continuous flow, as the trades, bottlenecks, and problems will inevitably appear during execution. In these circumstances, it is up to the team to solve the problems and make work ready for construction. If the team is unable to do so, the Takt time plan will not be executable. Nevertheless, a Takt time plan may help to anticipate future work due to the standard zones and Takt times, and it also creates urgency to solve problems. If a team is not able to make work ready that the field requires, the simulation demonstrates that only time buffers will help the team.

Research and findings from this dissertation have been reported at the International Group for Lean Construction conferences. Numerous papers are also citing and expanding the research put forth in this dissertation (e.g., Sacks, 2016, Tezel et al., 2018, Heinonen and Seppanen, 2016, Vatne and Drevland, 2016).

11.2 Future Research Questions

The case studies and simulation identified several future research questions as important, but beyond the scope of the research.

11.2.1.1 Does Takt time planning improve the amount of work performed with continuous flow during construction?

One would expect that if a team attempted to schedule work with better flow, they would fare better than if they did not try at all. By comparing common activities between schedules of similar projects, it would be possible to assess if Takt time planning improves continuous flow during construction.

11.2.1.2 When is it okay to plan work into the schedule that does not immediately release work for others?

Pull planning is a step forward from a top-down plan developed by a single scheduler, as it collaboratively plans the work (with those who will perform the work) that immediately releases work to others, but in some circumstances, is it favorable to plan work into the schedule that does not immediately release work to others? The following are three hypotheses to test in the future:

- It may be favorable in some circumstances to plan work into the schedule that does not immediately release work to others to balance production.
- There must be a lower boundary in task definition provided in a pull plan, and if a team explores beyond that definition, there is likely planned work that does not immediately release work to others.
- When a team pull plans, they are making assumptions about where the work sequence applies. For example, a team may pull plan a set of ten floors using the first floor as typical, when in fact, the network logic may vary in accuracy in some areas. Thus, pull planning will require another level of planning for the specific activities on each floor to account for the variance in work between floors.

11.2.1.3 How does work density change between trades and phases, and what are the impacts?

Buildings are made of millions of different components. A simplification that helps to gain perspective on the amount of work each trade activity has, is to total all of the different types of components within a given trade scope, then assign a total duration for how long that work will take to install (assuming certain crew sizes, work methods, and logistics). This can be performed per floor, per zone, or for the entire project. This provides a spatial distribution of the installation hours, and can indicate where some areas have higher work densities. The work densities likely change for different trades and phases, and may have different variation trends for larger areas on site. While obtaining this sort of data will result in an estimate, it is still a reference point to begin production leveling and developing zones. Related questions are: How close to perfectly level can a plan get for a given phase? What happens if a plan can't be leveled perfectly? What are the reasons for the variation? What percentage of the variation is preventable or absorbable through capacity buffering?

These early case studies provide a few indications. The first is that this problem is a worthy research topic alone. There is work density variation simply due to artifact design being done without considering production strategy. The building design should not necessarily suffer just to make the building construction more efficient, but there are certainly areas to improve upon by simply beginning design with a more detailed production strategy for a set of zones and a trade sequence for each construction phase. A testable hypothesis for future research is that each trade activity varies in a unique way to the other trade activities in the same phase of work, and there is no feasible zone configuration that perfectly levels work for all trades.

CHAPTER 12 REFERENCES

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CHAPTER 13 APPENDICES

13.1 APPENDIX 1: IGLC22 PAPER - AUTOMATIC GENERATION OF A DAILY SPACE SCHEDULE

Authors: Adam Frandson and Iris D. Tommelein

13.1.1.1 Abstract

Common challenges every project production team member faces in the construction industry when analyzing a schedule are to identify their workflow, opportunities for improving production, identifying production constraints, and communicating the plan to craftsmen in the field. Space scheduling is a tool to help visualize a critical path method (CPM) based schedule or a Line of balance schedule developed from the location-based management system (LBMS) method. Additionally, production teams require a current schedule. As such, this paper presents a program to generate and adjust a visual space schedule, by phase, for projects. This provides the production team with a visual control mechanism, a means to perform space conflict and sensitivity analysis, daily goal tracking, and can be a starting point for more detailed 4D CAD analysis. The space scheduling mechanism was applied during pre-construction and is currently used in the construction of an urgent care in northern California at an existing hospital. Results from pre-construction showed that twenty additional days (14% of the schedule) were identified in the space schedule as potential savings. Expected results from construction are improved productivity due to the daily level goal setting and detailed space scheduling; increased communication between trades due to the interconnectedness of their individual schedules; and an increased awareness of the production plan and work flow at a daily level by trade partners due to the visual schedule.

13.1.1.2 Introduction

The planning and scheduling of a construction project is a wicked problem (Rittel and Webber 1973). A construction schedules must meet several constraints. A schedule must meet the customer's completion time demand, yet meet or exceed budget constraints; the schedule must meet a logical sequence of activities, yet allow for subcontractors to work continuously and efficiently; the schedule should be detailed enough to be project-specific, yet easy to control and update; it must maintain a safe environment and provide enough time for quality installation. Thus, finding an optimal solution is likely impossible. Applying buffers between activities is one strategy to manage the complexity and uncertainty in a schedule (Howell et al., 1993). Providing work access, required coordination with trades, and design constructability are a few of the most common reasons for why time buffers are applied in construction projects and why accounting for space in the schedule is important (Russell et al., 2013). Research also shows that failing to account for space as a resource in the schedule may lead to major productivity losses (Akinci et al., 1998).

The program presented in this paper developed out of a need to communicate how the different trade partners moved through the construction space during each phase of interior construction. The interior phases of work followed the overhead, in-wall, and finish "parade of trades" (Tommelein et al., 1999). The project was a $3-million dollar, partial-floor retrofit of an urgent care in an existing healthcare facility. The project used an integrated form of agreement contract, the Last Planner System, and Takt time planning (Frandson and Tommelein 2014). The research described here uses an action-based approach to test a solution to improve communication of the production schedule by making the schedule visual. The objectives of communicating the production schedule were to identify how the resource space was used in the schedule (including how it was used as a buffer); analyze the space schedule for improvement opportunities and space-time conflicts; aid the process of creating "complete kits" of work for each activity (Ronen 2007); and make the information accessible to the superintendent in the field.

13.1.1.3 **Background**

Line of balance technique is one way to account for space in a construction schedule. Line of balance technique was used in 1931 in the Empire State Building's project production system from design document completion (per-floor) to construction of the building (Willis and Freidman 1998). The Line of balance technique in this research was used in context of the Last Planner System™ (Ballard 2000). The Takt time planners produced a Line of balance schedule after each Reverse Phase Schedule (RPS) meeting to help optimize the schedule when the entire production team reviewed the Reverse Phase Schedule schedule the following meeting (Frandson and Tommelein 2014).

While Line of balance technique provides a clear representation of the production schedule and the associated activity's production rates, there are several other factors to consider when planning for space allocation. Thabet and Beliveau (1994) identified three classes of space demand for each activity. Class A activities require the entire space scheduled to itself. Class B activities require a fixed amount of space but not the entire space such that other activities may be scheduled concurrently providing the space exists. Class C activities are activities that require staging of material before the activity begins. The research also acknowledged the relationship between productivity versus scheduling work in congested environments and provides a method to model space use. Bonnal et al., (2005) classified activities as linear space-constrained, discrete space-constrained, or non-space-constrained. Tommelein and Zouein (1993) provided a tool for managing and modelling changes to temporary facilities, material flow, and equipment use on projects. Riley and Sanvido (1997) presented a 16 step method for Space planning. The method reduced to four general steps are: 1. identify space constraints, 2. identify the space layout, 3. sequence the work, 4. resolve conflicts.

Due to the capabilities of building information modelling software, factoring space as a resource into the schedule has become more prevalent over the past decade. Hessom and Mahdjoubi (2004) identified the trends in 4D CAD beginning in the 1990s. One trend identified that still exists today is that 4D CAD is primarily used as a communication tool to explain design and construction plans. Since 2011, Autodesk provides this 4D capability in Navisworks (Autodesk 2011). Akinci et al., (2002) aimed to automate the generation of a 4D CAD simulation that performed more detailed time-space conflict analysis using unique industry foundation classes for elements which considered both the space required method to install different building components. This research performs a similar time-space conflict analysis based off the 2D floor plan rather than the BIM model to meet the last objective described in the problem definition section.

13.1.1.4 Daily Space Scheduling Program

Realization of a need and problem definition

Takt time planning began before the first Reverse Phase Schedule meeting (Frandson et al., 2014). The Takt time planners held one-on-one meetings with the trade partners and discussed their desired workflows. Workflows are the movement through the construction space and may be characterized in several ways. The trade partners characterized their work in two ways: 1) directionally (e.g., clockwise, North to South, left to right, etc.), and/or 2) in relation to objects (e.g., work from the vertical shafts out to the perimeter, work out from the electrical room, etc.). The Takt time planners considered these workflows and characterized them as movements through zones. Prior to the first Reverse Phase Schedule meeting, the Takt time planners produced a series of visuals characterizing the workflows for the work flows for the mechanical, electrical, piping, drywall, and fire sprinkler trades through zones of work.

The team sequenced their activities and associated workflows through the zones for each phase via the Reverse Phase Schedule process. Follow-up meetings used the Line of balance technique to account for space using Vico Control (Vico 2009). The Takt time planners did not use actual quantities of work from the BIM model, but rather the crew size and durations from the pull plan to populate the Line of balance schedule. While the resulting schedule did not tie back to the quantities in the building information model for the project, the schedule was still useful in identifying areas to improve the scheduled generated from the pull planning process. Using Vico Control 2009 in this way also acted as a proof of concept for the general contractor, for they had the software but had not used it on a project before.

While the Line of balance schedule accounted for the movement through the zones in the desired sequence for each trade, the Line of balance schedule failed to communicate what the zones actually looked like to the trade partners and the trade partners were much more receptive to the initial colored floors plans generated prior to the Reverse Phase Schedule meetings. Generating the colored floor plans took a considerable amount of time because it was a manual process of translating the Line of balance schedule onto a series of floor plans. The Takt time planners considered a 4D approach to this problem, but decided against it as it would require maintenance to remain current and it would cumbersome to implement directly in the field without installing a computer. As such, the team identified a need to develop a tool to automatically create the schedule in a visual format (i.e., the daily space schedule). The objectives of the space scheduling program (problem definition) were to communicate the following: (1) the activity performed, (2) who is performing it, (3) where the activity is performed, (4) when they are performing it, and (5) the immediate effects if the work is not completed in the allotted time (conflict analysis). Last, the output of the program must also be printable and easy to use by the superintendent on the project.

Figure 13-1 reflects the information flow for the production and distribution of the daily space schedule. The information flow follows the 4 step procedure outlined by Riley and Sanvido. Input information for the space schedule came from the initial pull plans from the Reverse Phase Schedule meetings, thus there was a separate daily space schedule for each phase of work. The Reverse Phase Schedule meetings also identified the non-space constrained activities that are in the actual construction schedule but not on the daily space schedule. Activities were made ready and committed to in the weekly commitment planning meeting.

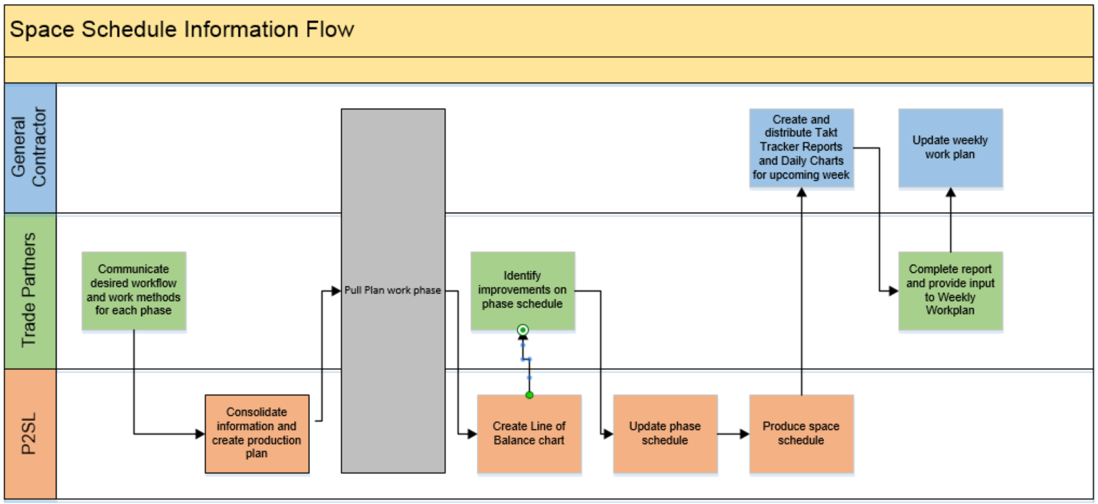


Figure 13-1 – Information flow for production and distribution of space schedule

Contents and output of the daily space scheduling program

The daily space scheduling program is a set of modules developed in Microsoft Visual Basic for Applications 7.1 for Microsoft Excel (Microsoft 2012). The program creates a colored-up floor plan for every trade, every day, and lists the activity performed. Figure 13-2 is an example excel output for 3 days of work for 3 trades. When zoomed out, the entire space schedule for a phase is viewable (Figure 13-3). The program will also format the floor plan to print to pdf and can be uploaded onto an iPad to use in the field. Figure 13-4 shows an example of multi-page view of a space schedule used on site.

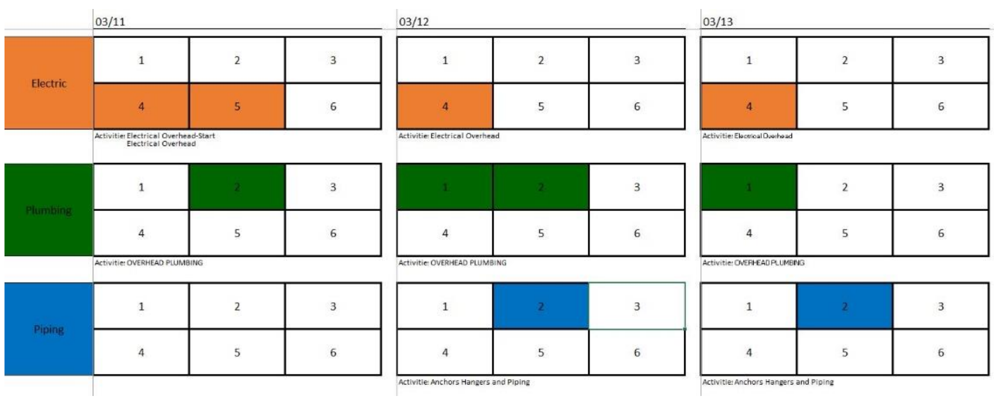


Figure 13-2 – Example output for 3 days of work for 3 trades for a 6-zone floor plan

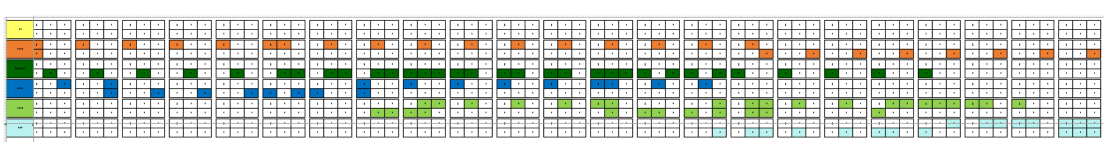


Figure 13-3 – Example output for an entire phase of work

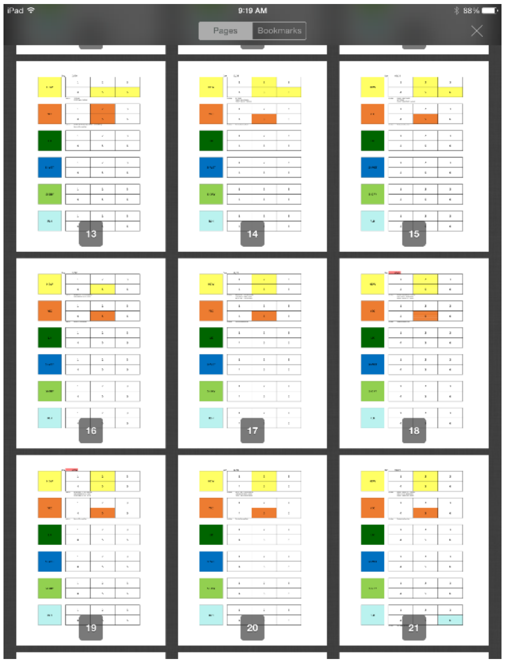


Figure 13-4 – Example of virtual output of software viewed on an iPad

13.1.1.5 Required Inputs and How the Program Works

Figure 13-5 is an IDEF0 diagram for the initial creation of the daily space schedule. The program requires four inputs from the user: a construction schedule, the configuration of the zones on the floor, the suppliers' names and their associated colors. When the schedule is imported, the user will have to identify if any names require conversion.

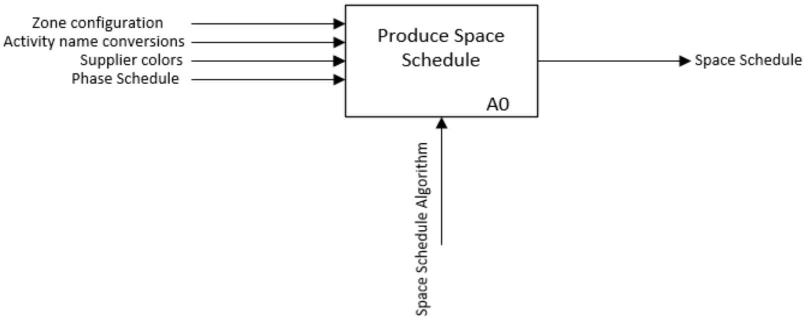


Figure 13-5 – IDEF0 Diagram of Space Schedule

Creating the daily space schedule is a six-step process.

- **Zone configuration** (Figure 13-6) – Create the zone configuration in the designated 12x18 grid within excel.

- **Name the suppliers and their colors** (Figure 13-7) – The names are case sensitive and need to align with the schedule imported. If the imported schedule does not have a supplier column or it is incomplete, then a new column must be created reflecting this information inside excel.

- **Name the zones** (Figure 13-8) – The daily space scheduling software requires a means to align the zone names in the zone configuration with the zone names used in the schedule.

- **Import the schedule** – At a minimum, the imported schedule must contain the activity name, the supplier, start and finish dates.

- **Convert activity names to zones** (Figure 13-9) – This step developed out of necessity. The names of activities vary depending on the location hierarchy designated in Vico Control. This step acts a double check to make sure that the program will identify all the correct zones and make sure the zones variables are the correct data type.

- Run "Create the charts" and "create the zones".

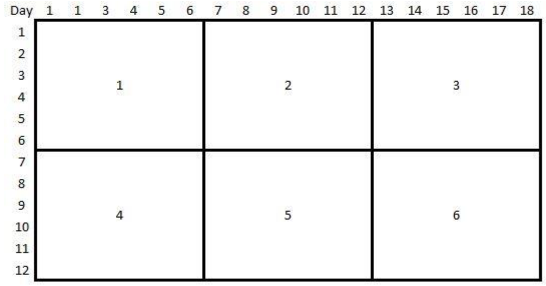


Figure 13-6 – Step 1: Zone configuration

Supplier Name
Drywall
Electrician
Plumber
Piping
Ductwork
Firesprinkler

Figure 13-7 – Step 2: Name and assign supplier colors

Zone Names		Zone Count:	6
Zone1	1		
Zone2	2		
Zone3	3		
Zone4	4		
Zone5	5		
Zone6	6		
Zone7			
Zone8			
Zone9			
Zone10			

Figure 13-8 – Step 3: Name zones

Unique Name list	Zone Assignments
DRILL AND ANCHORS ALL TRADES	
TOP TRACK	
PRIORITY WALL AT DUCT FRAMING	
Priority Wall at Duct Framing Zone 5	
5->1	5
Priority Wall at Duct Framing Zone 2	
2->1	2
PRIORITY WALL FRAMING	
PRIORITY WALL MEP ROUGH IN	
BOXING AND STUBBING (ELECTRICAL AND PLUMBING)	
ELECTRICAL OVERHEAD	
Electrical Overhead-Start	
Electrical Overhead	
FRAMING INSPECTION	
2->2	2
5->2	5
SOFFIT TRACK	
PRIORITY WALL AT DUCT HANGING	

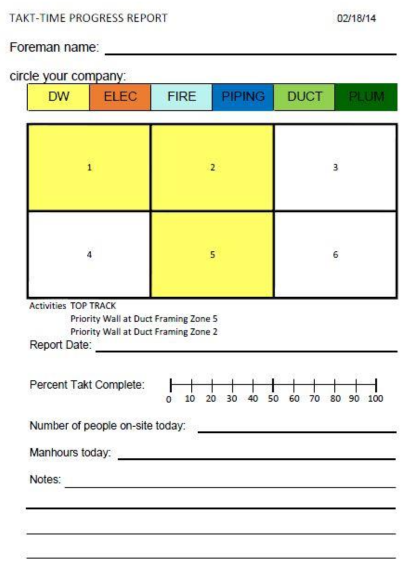
Figure 13-9 – Step 5: Convert activity names

Creating the initial charts runs a routine to identify the number of suppliers (n), the zone configuration, and the number of days in the schedule (m). A second routine sets up a blank grid of (n x m) floor plans so that space can be allocated to any supplier for any day. The last routine identifies all weekends in the schedule.

Creating the space schedule first runs a routine for every activity to identify the zone, supplier, start date and end date. Second, for every day an activity occurs, set the zone in the correct "supplier-day" floor plan the supplier-specific color and add the activity to the list.

13.1.1.6 **Controlling and Updating the daily Space Schedule**

The activities identified in the daily space schedule all derived from activities in the construction schedule. The activities in the construction schedule were decomposed and made ready via the Lookahead process. Activities that were made ready appeared on the work plan for the week and accompanied by a daily colored-up progress report generated from the daily space schedule (Figure 13-10). If activities were not made ready or the schedule changed, the daily space schedule could be updated in quickly in the excel file by importing the schedule update.


TAKT-TIME PROGRESS REPORT 02/18/14

Foreman name:

circle your company:

DW	ELEC	FIRE	PIPING	DUCT	PLUM

1	2	3
4	5	6

Activities TOP TRACK
Priority Wall at Duct Framing Zone 5
Priority Wall at Duct Framing Zone 2

Report Date:

Percent Takt Complete: 0 10 20 30 40 50 60 70 80 90 100

Number of people on-site today:

Manhours today:

Notes:

Figure 13-10 – Takt time progress report output from daily space schedule

13.1.1.7 **Results**

The researchers successfully produced program, which produced a daily space schedule that was easy to update and control. The senior project manager, project manager, five foremen, and owner's representative were all included in the evaluation of the solution (Table 13-1 –). Overall, the space scheduled was appreciated by the team. A few critiques on the program were: difficulty in initial setup, lack of a detailed floor plan, and difficulty in scaling the space schedule to multiple floors while maintaining the same level of detail. Overall, the entire team felt the tool accomplished the overall goal of making the schedule more visual.

Evaluation Survey	Low	High	Median	Average
Innovation	2	4	4	3.6
Performance	3	5	5	4.1
Usability	3	4.3	4	4.3
Reliability	3	5	4	4
Flexibility	3	4	4	3.6

Table 13-1 – Results of Daily space schedule survey.

The schedule duration for the phase of construction the space scheduling tool was used for was 146 work days. The production team identified 20 days out of the 146 days as potential savings or opportunities to improve the schedule. Of the 20 days, 10 days were directly identified in the daily space schedule across the three phases of work and 10 days were identified from the Line of balance schedule after the daily space schedule was created for the phase. Alone, the Line of balance schedule identified available space, but it was not possible to identify if new sequences of work were feasible from a work flow perspective for the individual trades. As such, the representation of the zones on the floor plan was critical to validating potential schedule improvements.

13.1.1.8 **Conclusion**

This paper focused on the description and evaluation of a solution to a common challenge in construction: properly communicating the construction schedule to the entire project team. The current state for communicating the schedule was via a Gantt chart, Line of balance schedule, and manually created color-ups of the floor plan, called a daily space schedule. These mediums were used because of the project's work structuring method, Takt time planning. The trade partners valued the color-ups medium, so the researchers developed a program to automate the generation of the daily space schedule. From the daily space schedule and the clarity it provided when associated with the Line of balance schedule, 20 days out of the 146 work days were identified as potential days to improve the schedule without incurring additional project costs. The tool was used in the field via an iPad and helped the superintendent identify impacts to the overall schedule if particular Takt time cycles were not completed on time. Limitations of the daily space program was that it did not produce a colored up floor plan, but rather a simplified colored version of the floor plan, and bugs in the initial set up of the program. Nevertheless, the research concludes that the daily space schedule helped the entire project team understand their own, and one another's, work flow during the entire interior phase of construction.

13.2 APPENDIX 2: SIMULATION FIGURE EXPANDED

Below is a key to the simulation model figures.

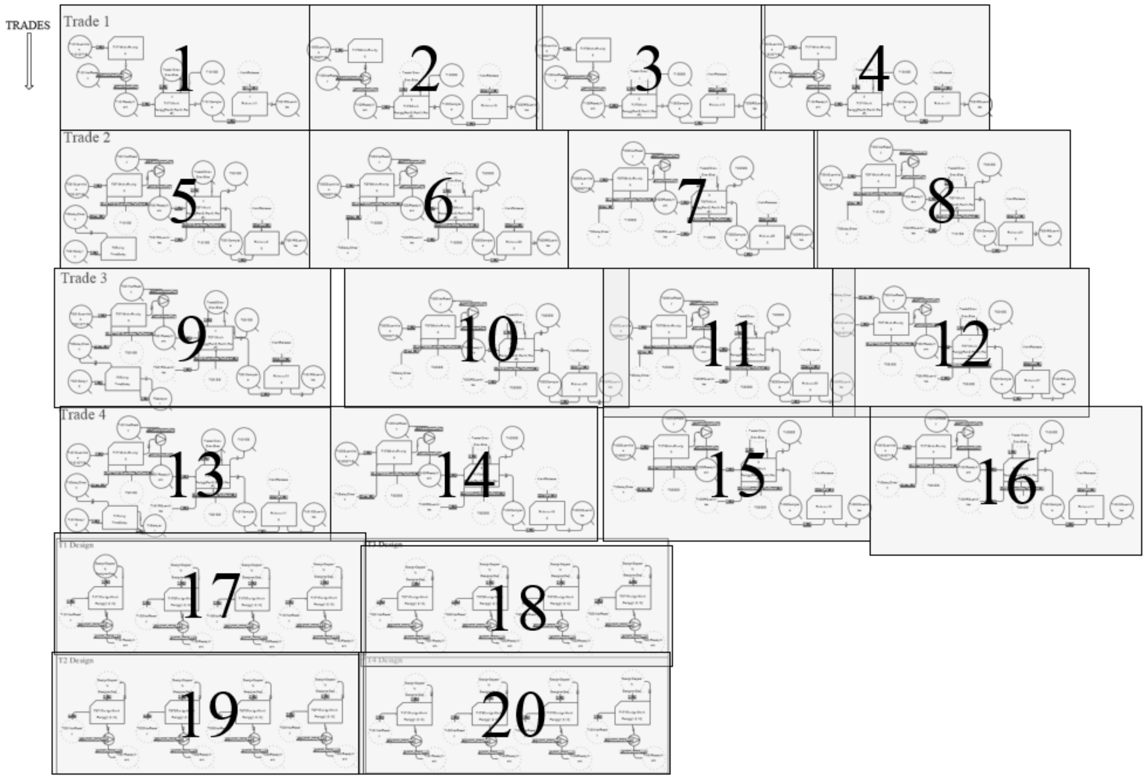


Figure 13-11 – Key to simulation model figures, each number is the figure number in the preceding figures labeled "Simulation Figure X"

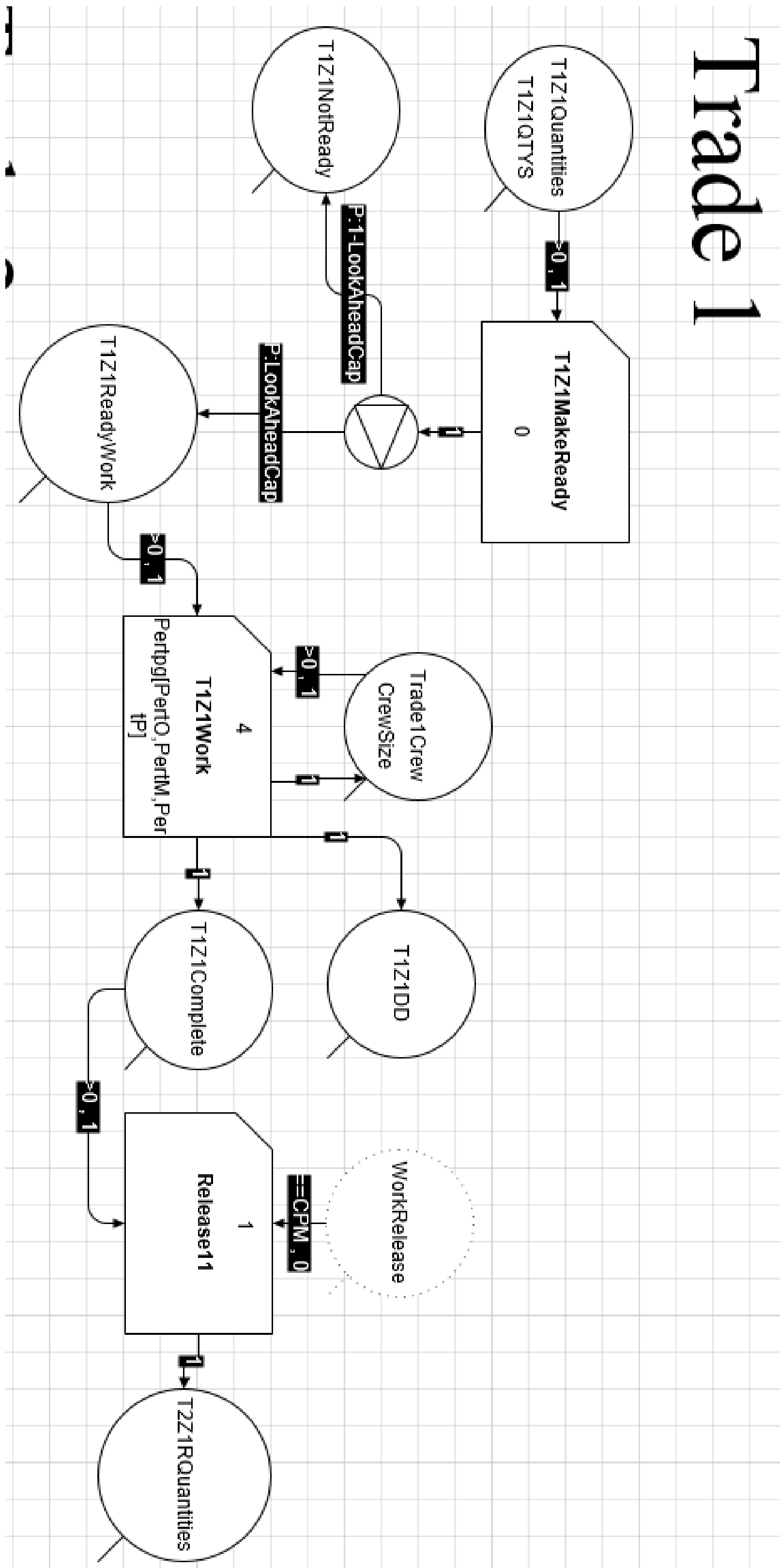


Figure 13-12 – Simulation Figure #1

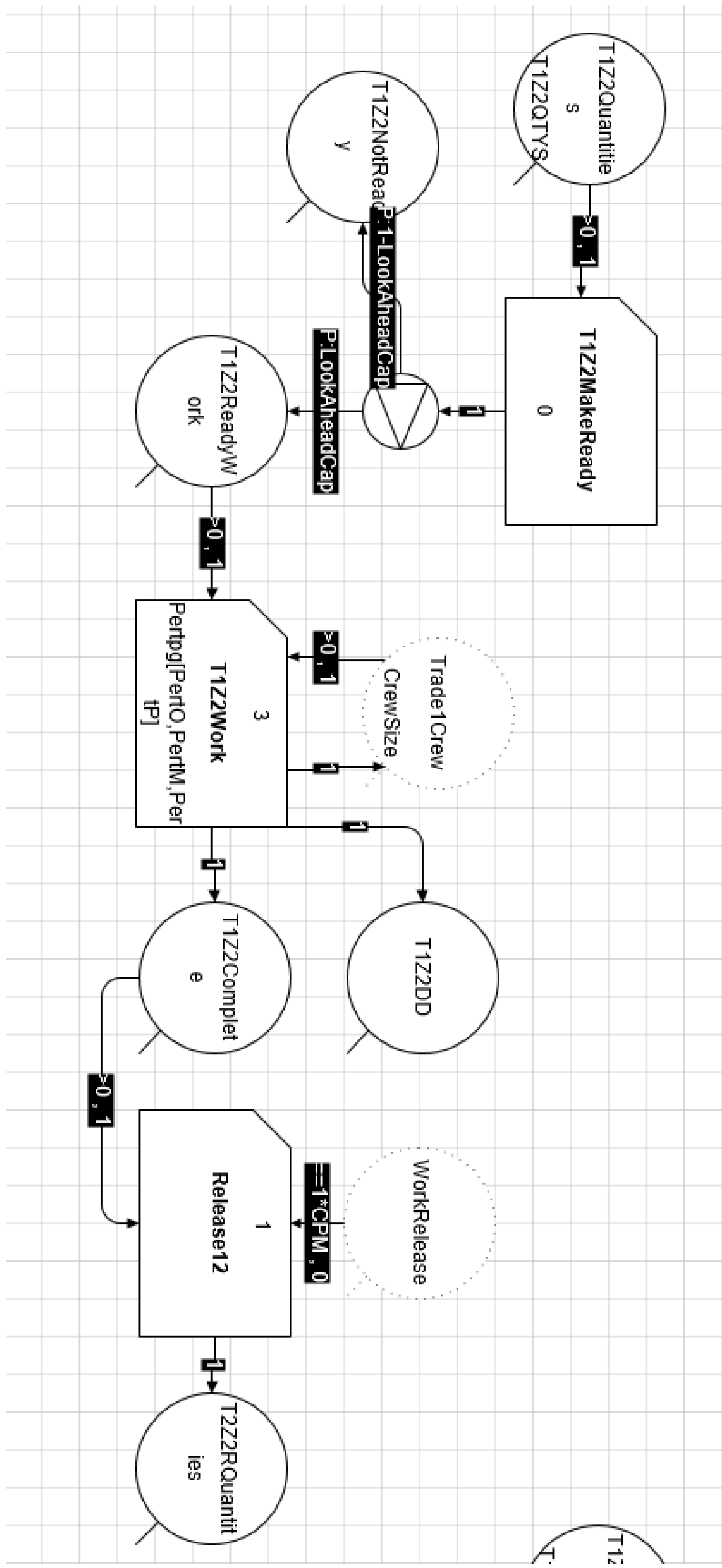


Figure 13-13 – Simulation Figure #2

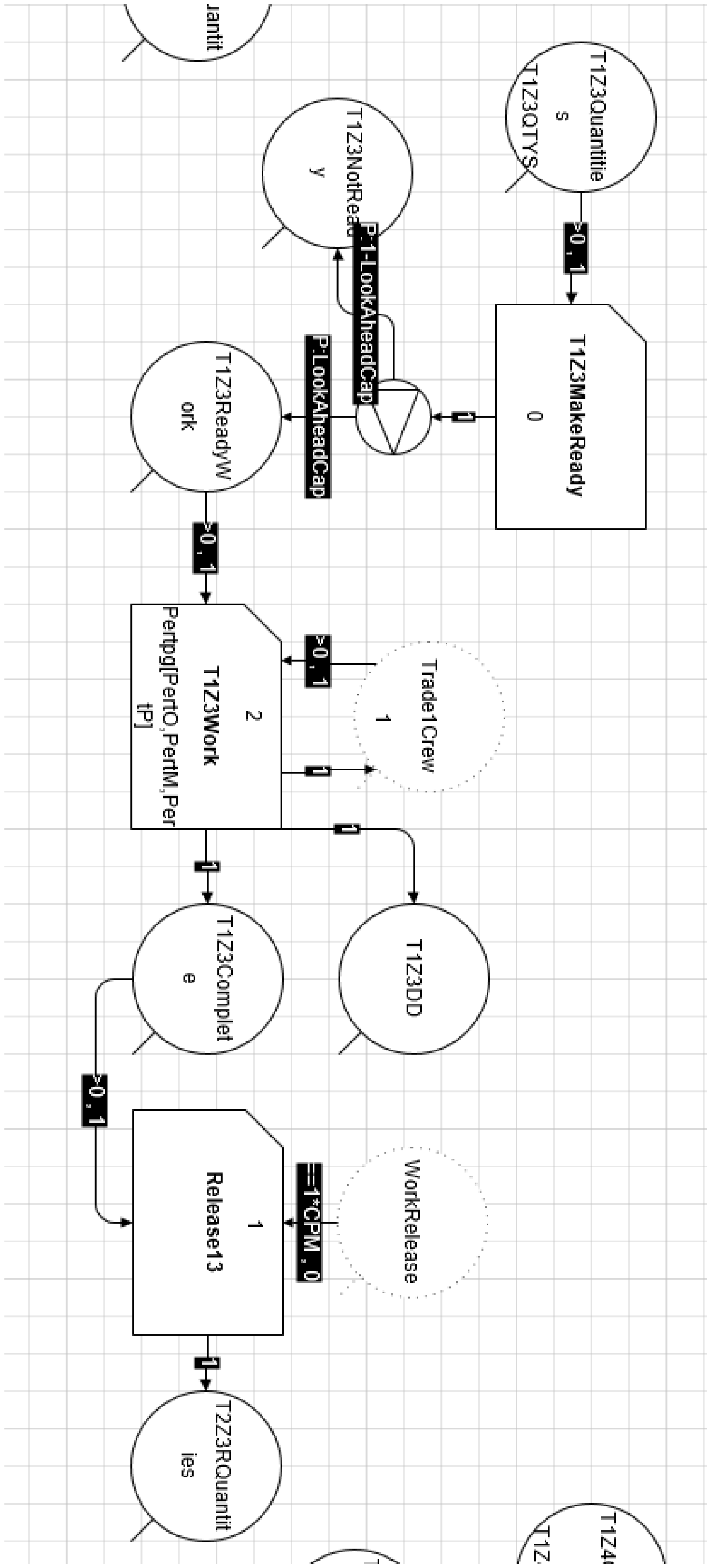


Figure 13-14 – Simulation Figure #3

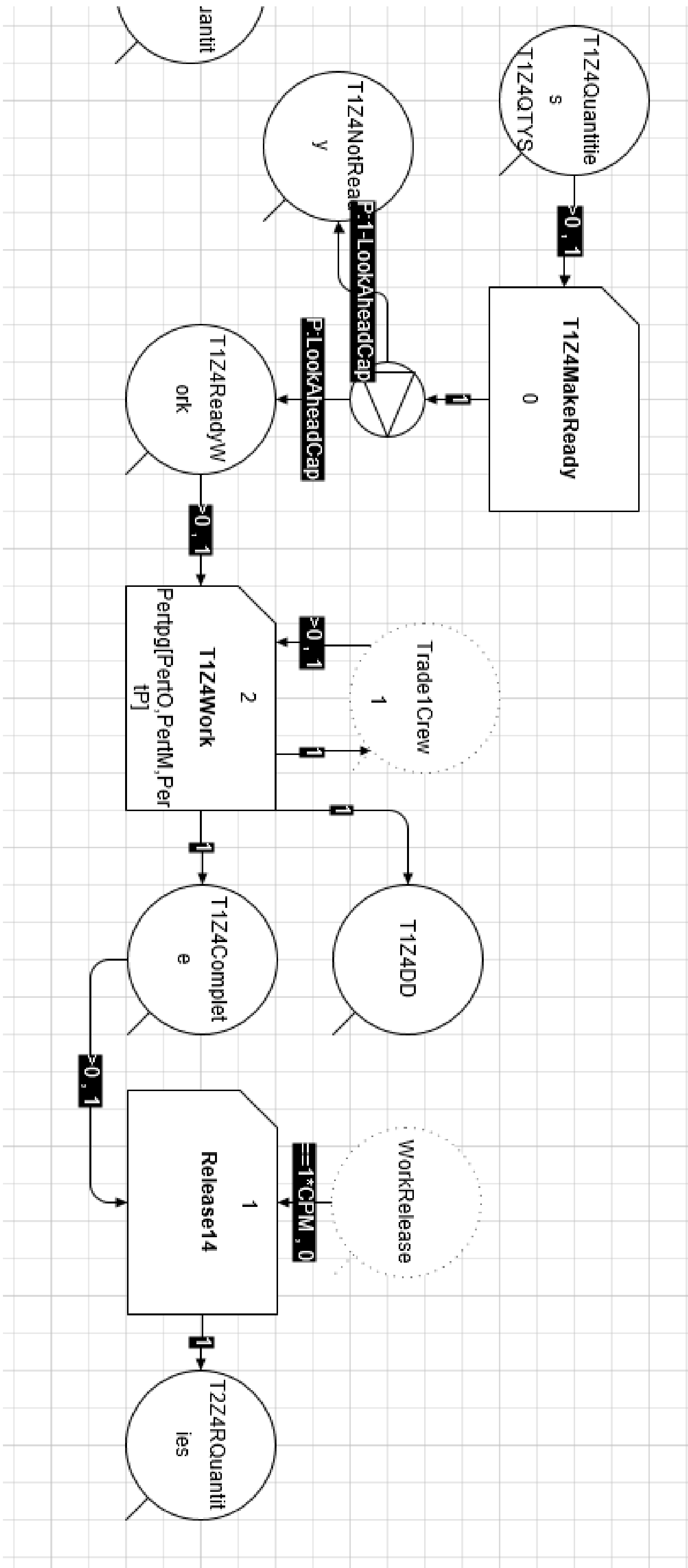


Figure 13-15 – Simulation Figure #4

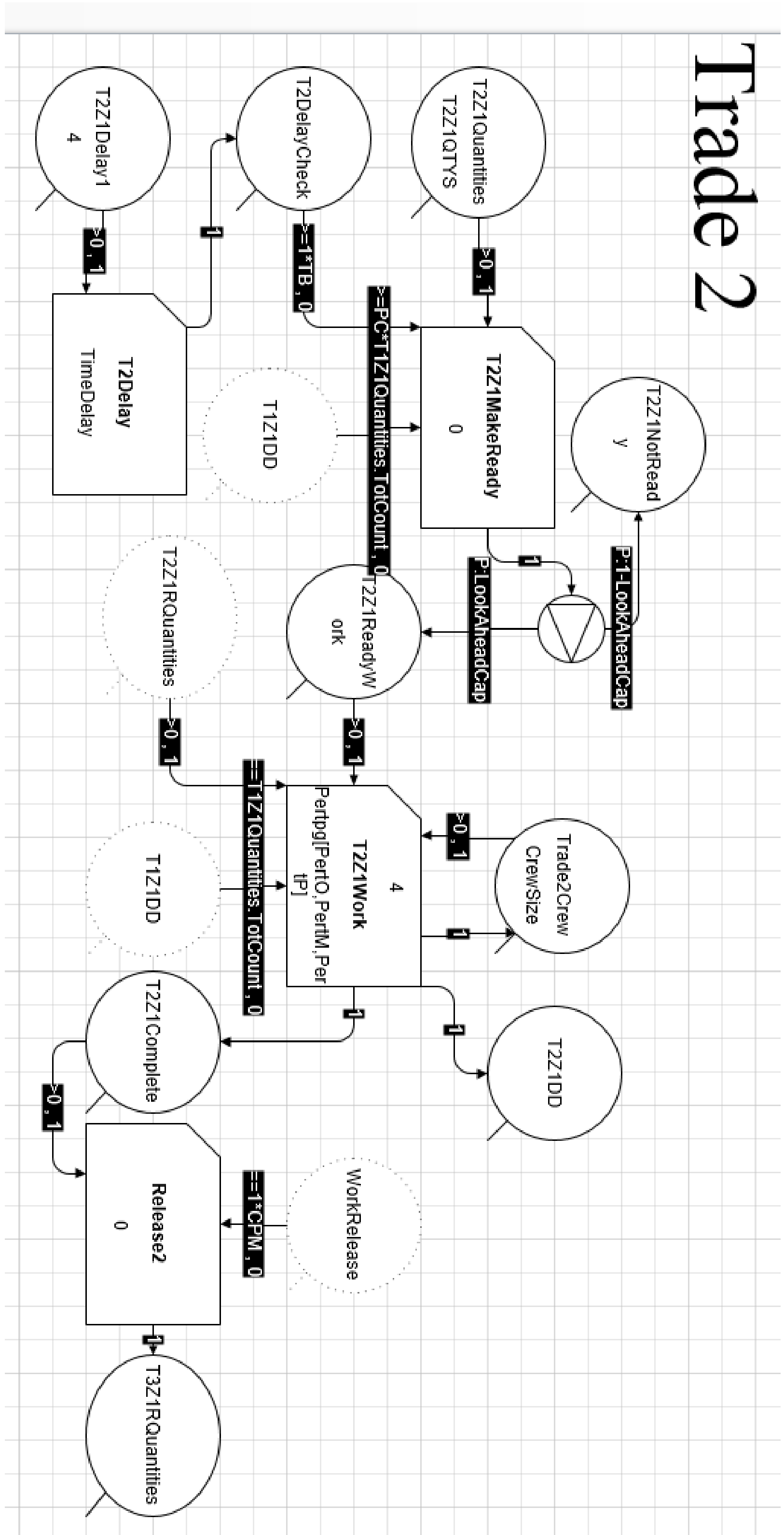


Figure 13-16 – Simulation Figure #5

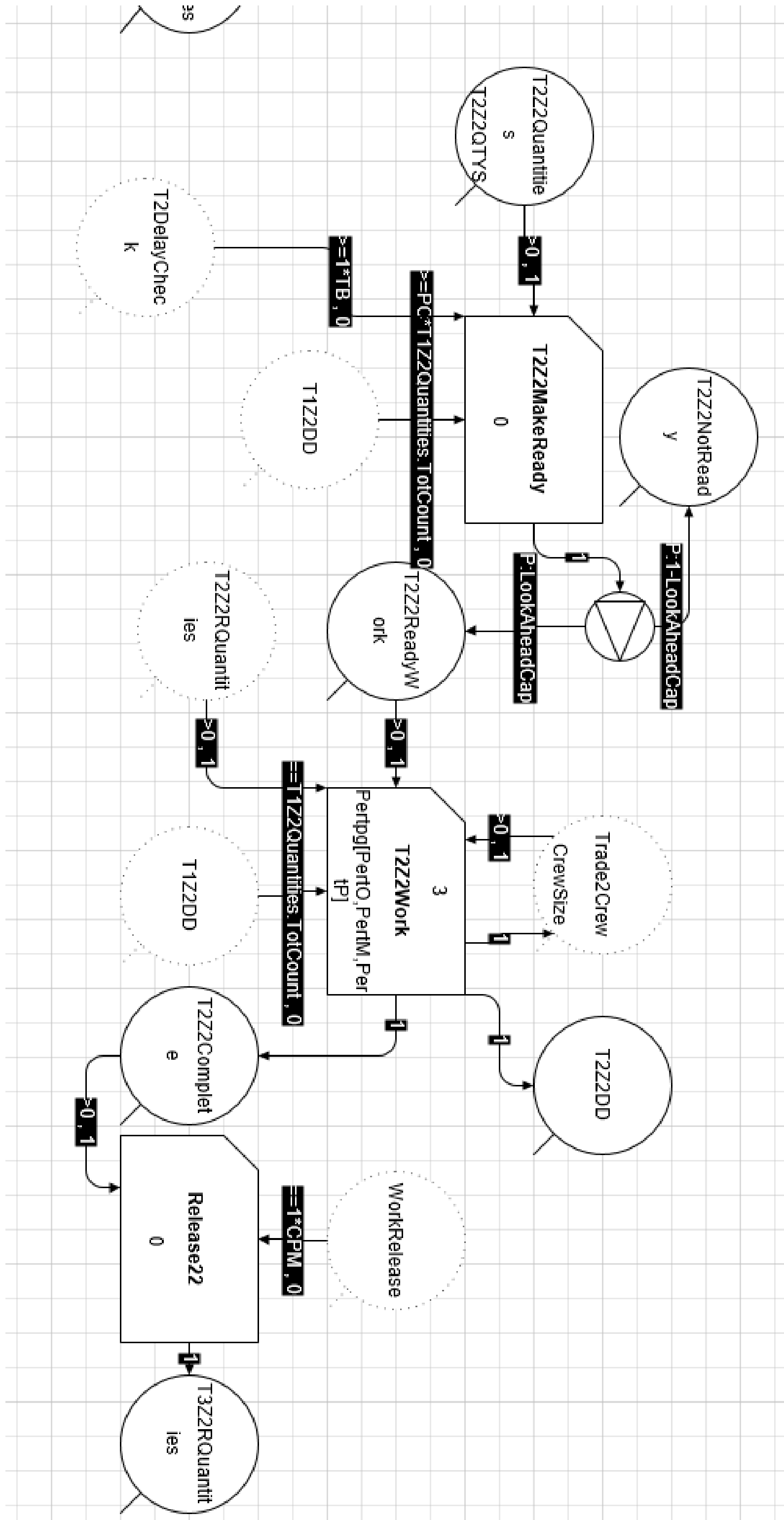


Figure 13-17 – Simulation Figure #6

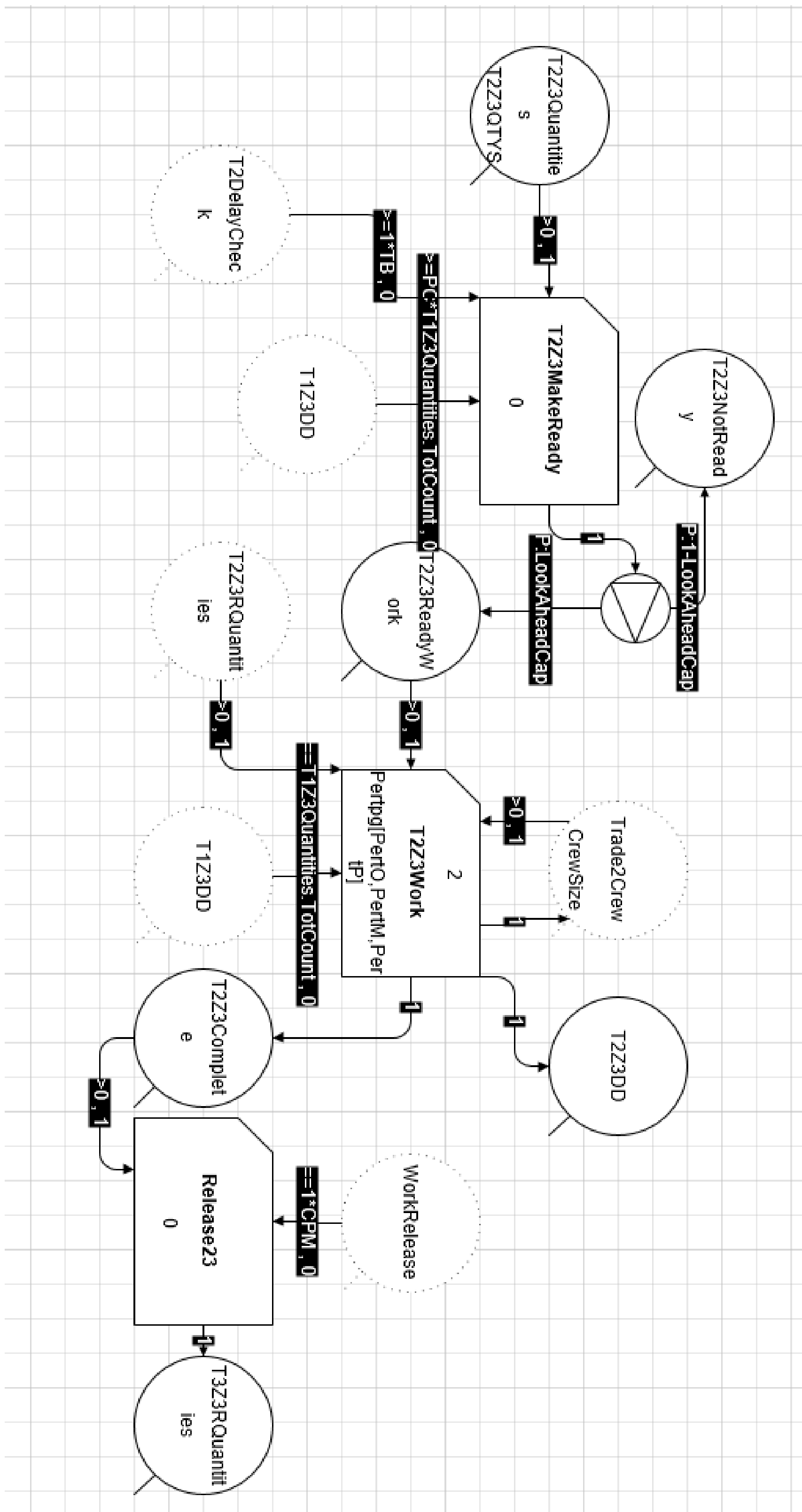


Figure 13-18 – Simulation Figure #7

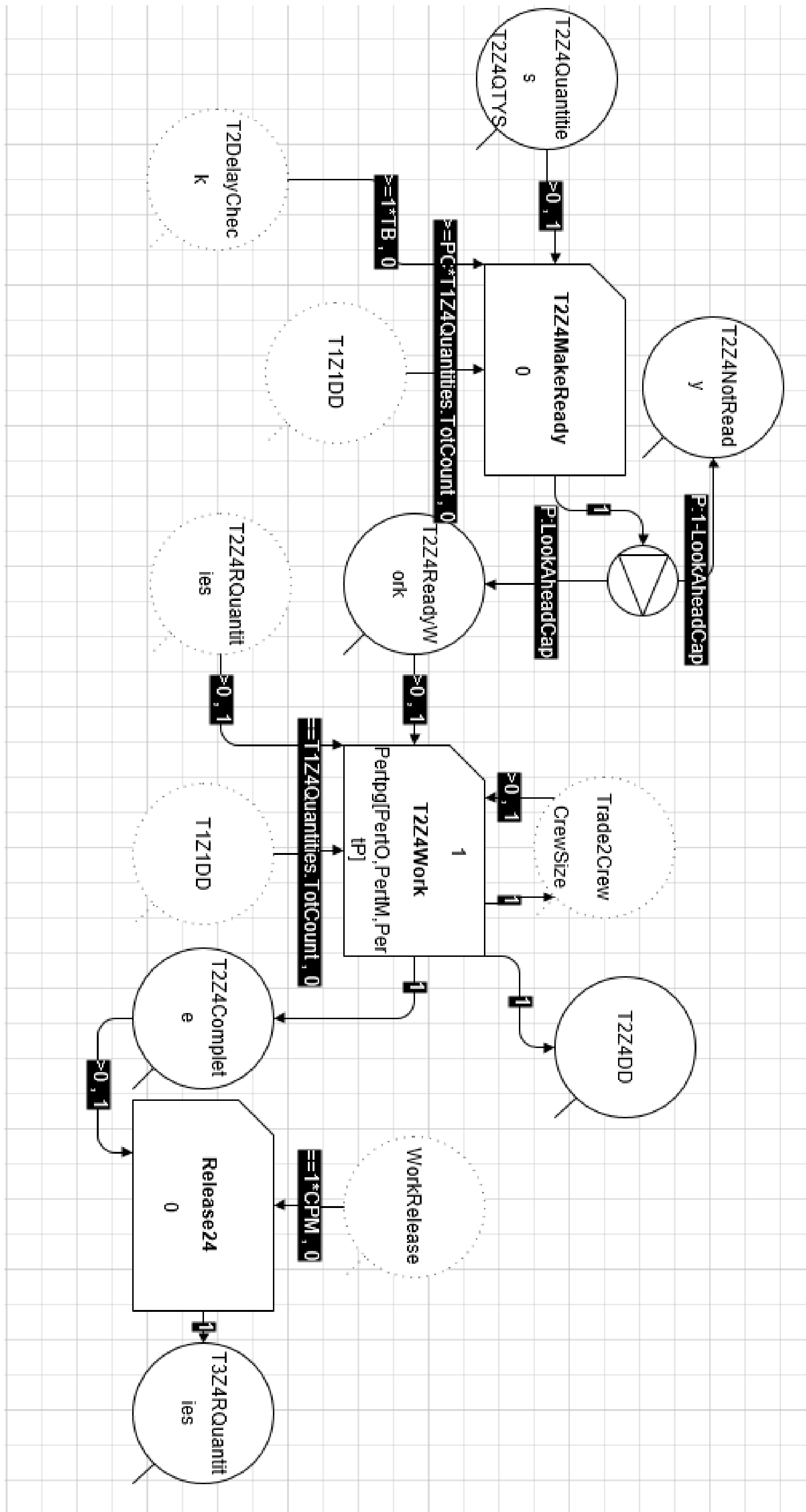


Figure 13-19 – Simulation Figure #8

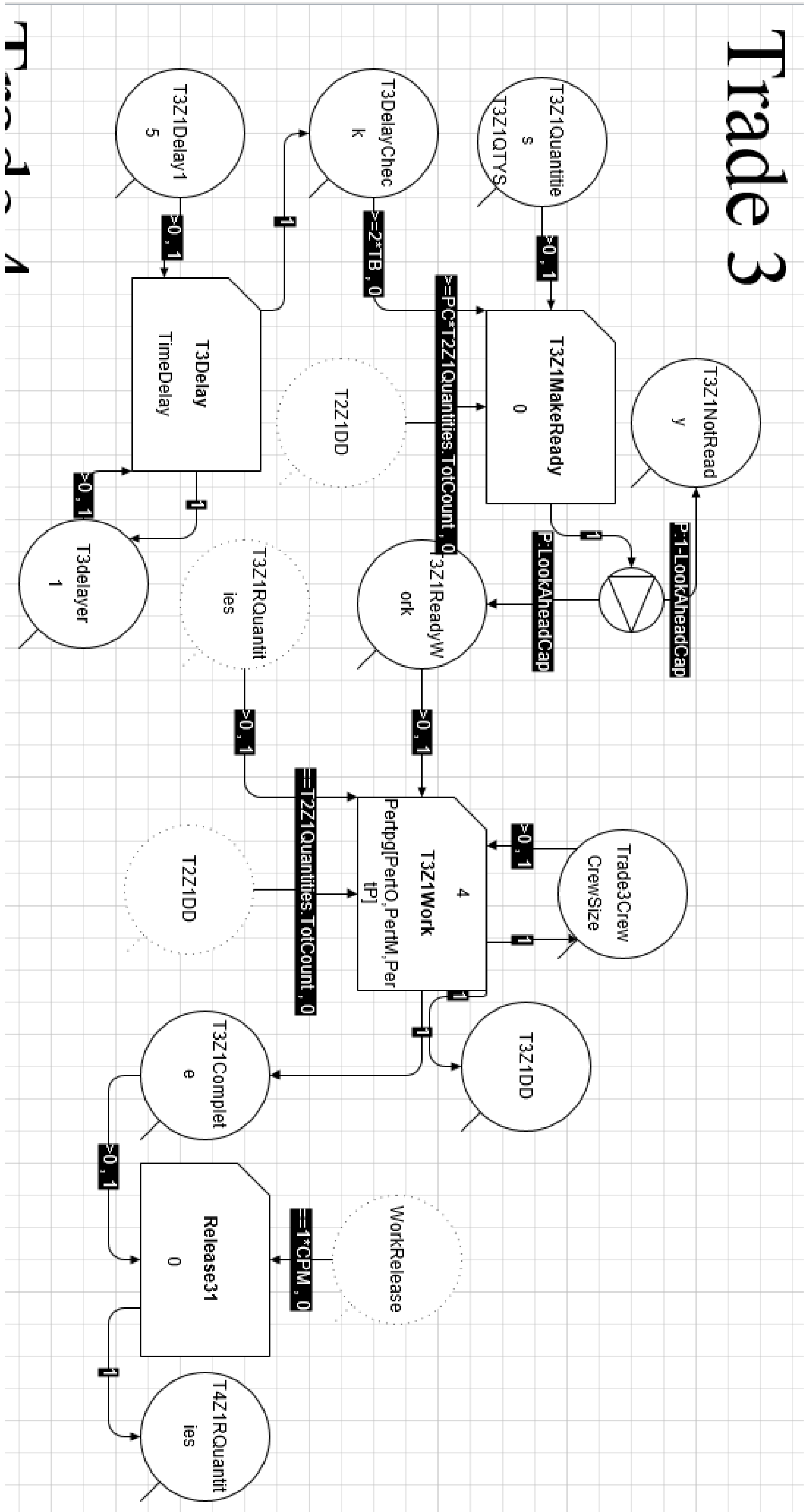


Figure 13-20 – Simulation Figure #9

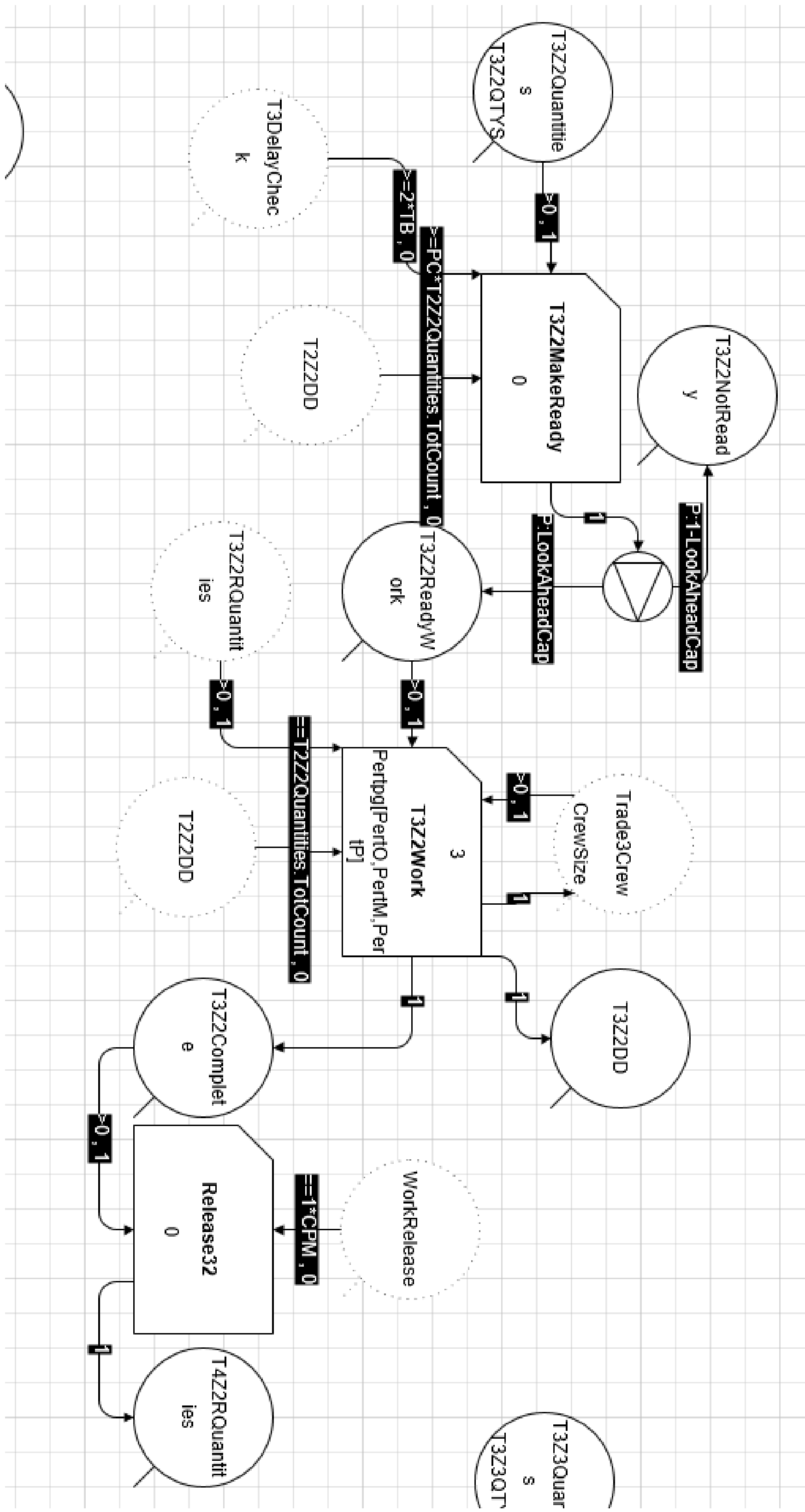


Figure 13-21 – Simulation Figure #10

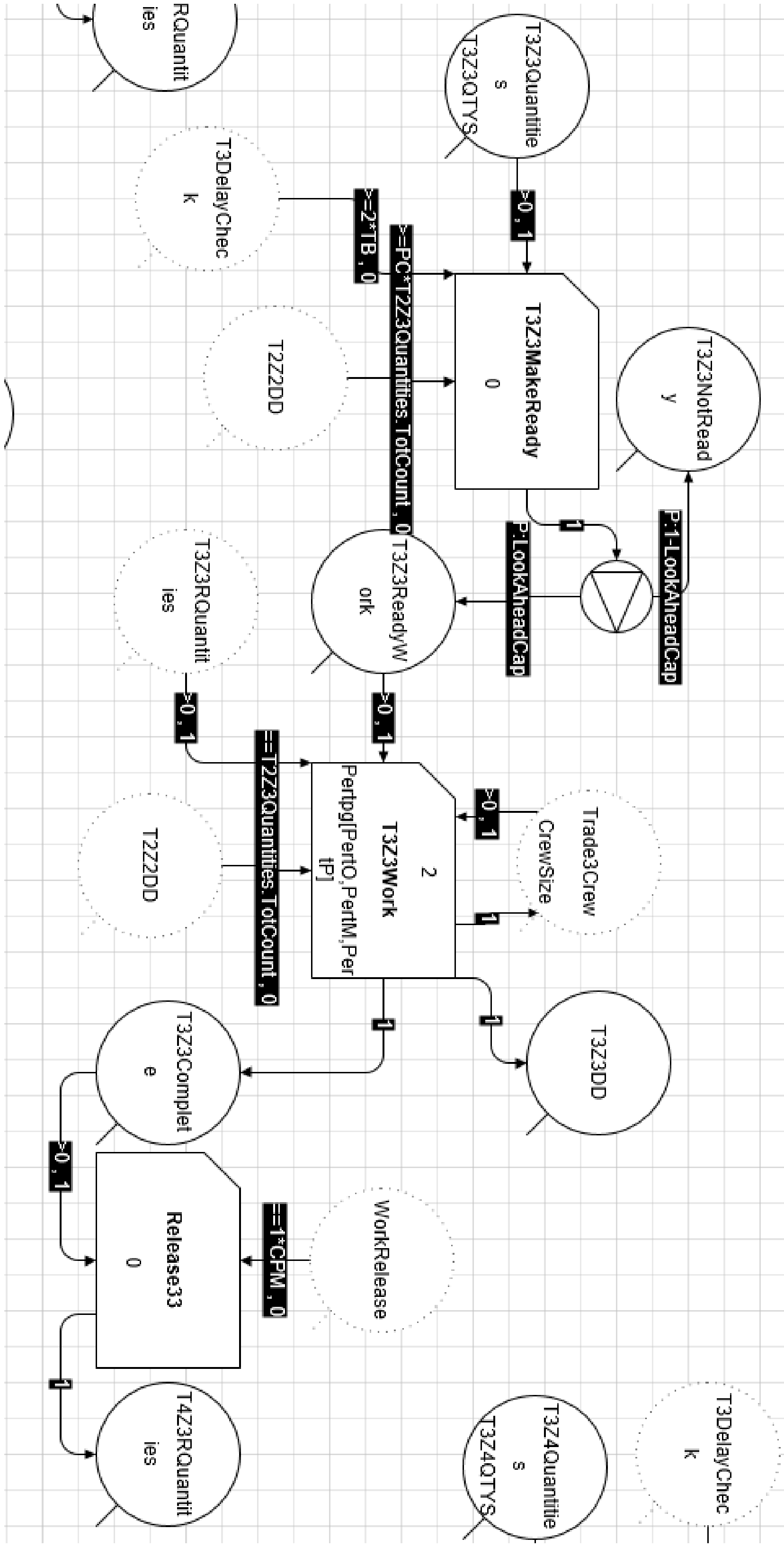


Figure 13-22 – Simulation Figure #11

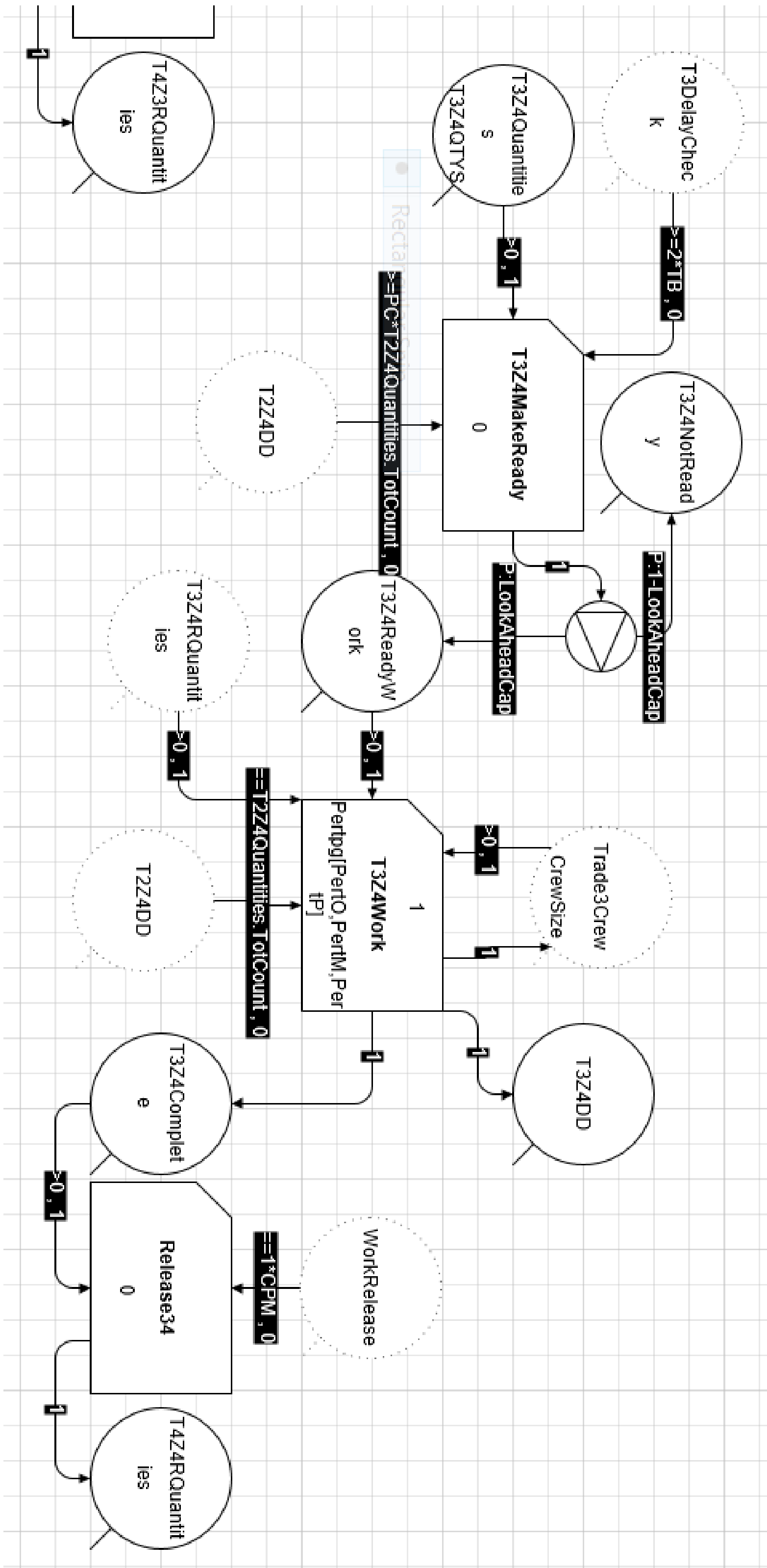


Figure 13-23 – Simulation Figure #12

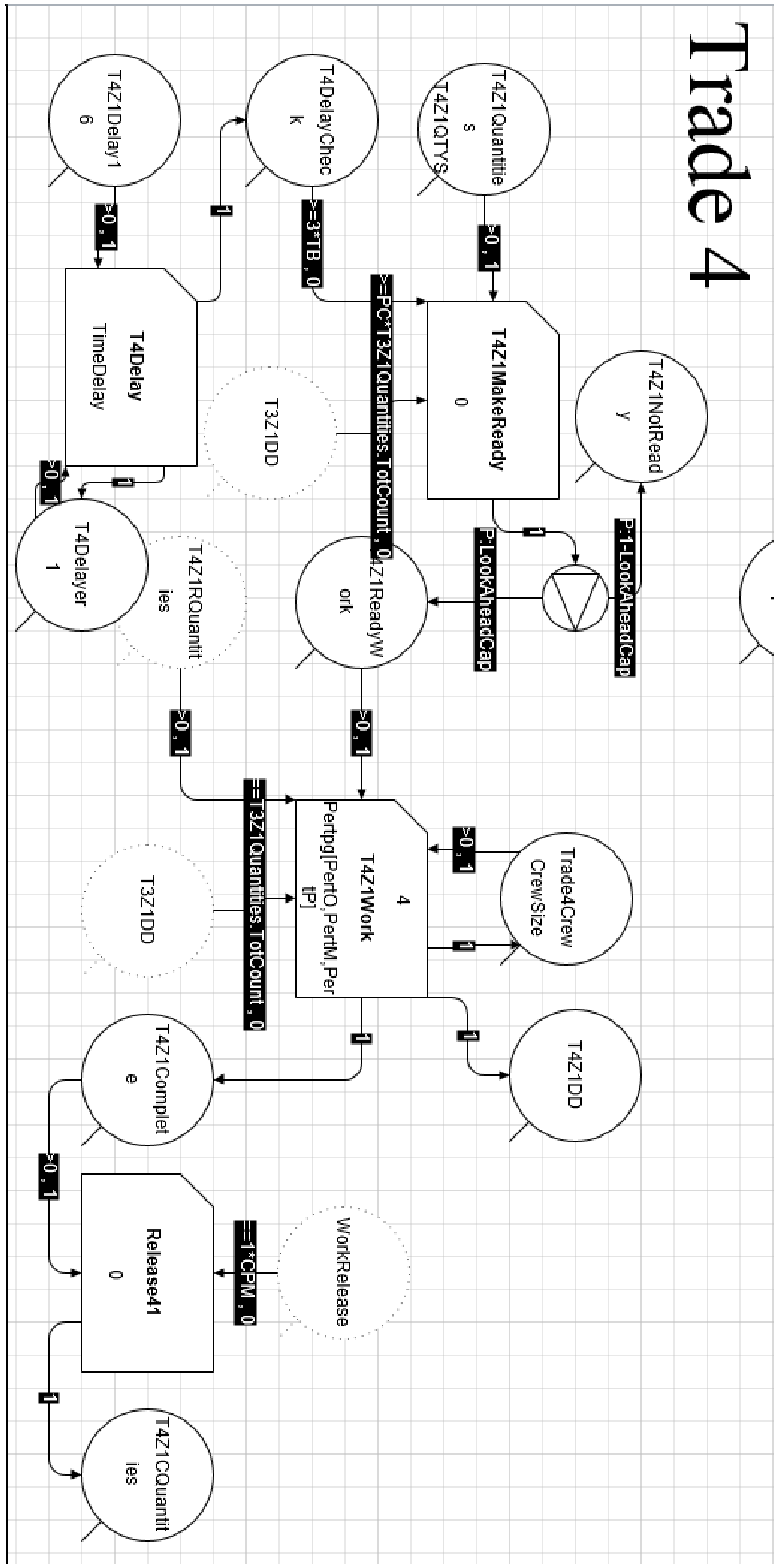


Figure 13-24 – Simulation Figure #13

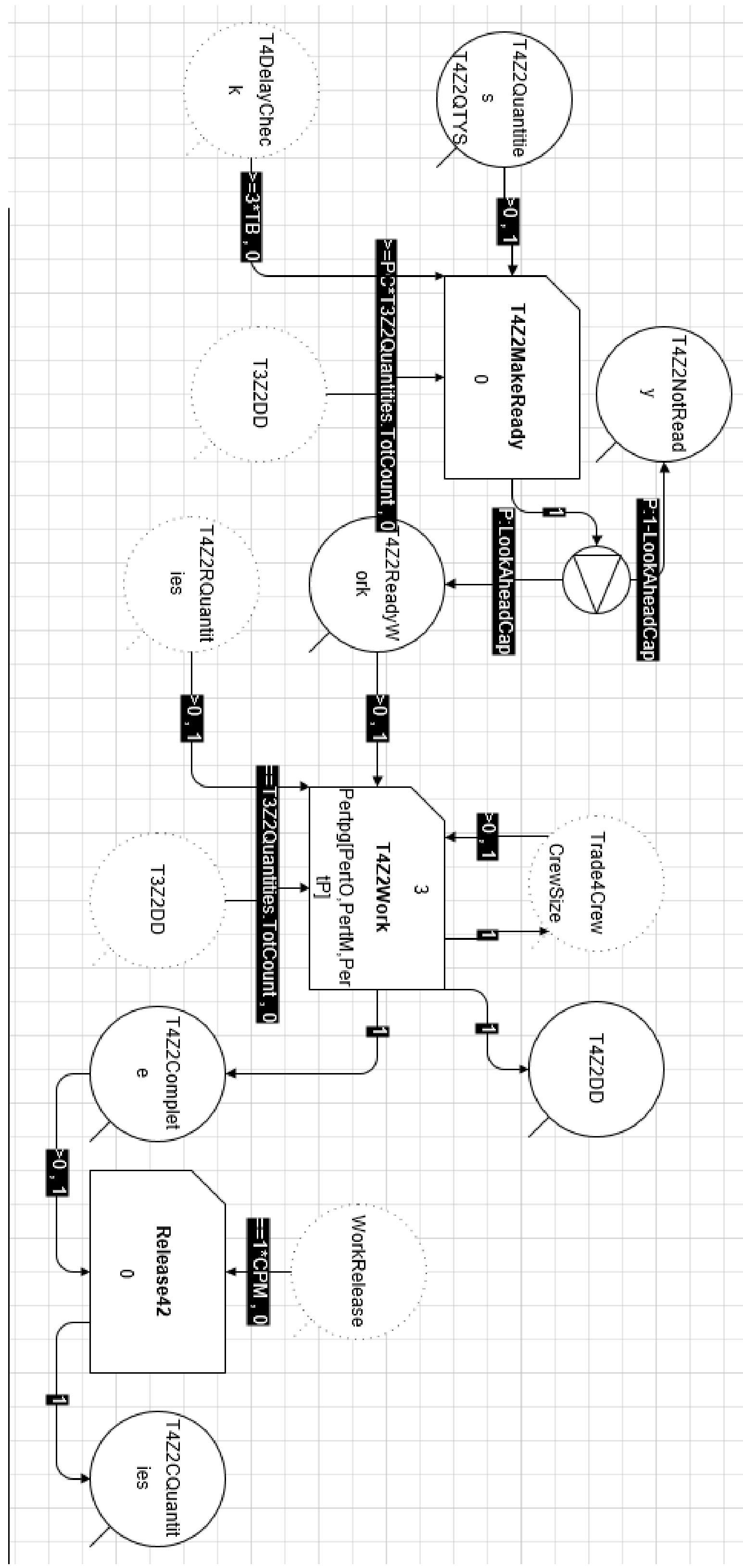


Figure 13-25 – Simulation Figure #14

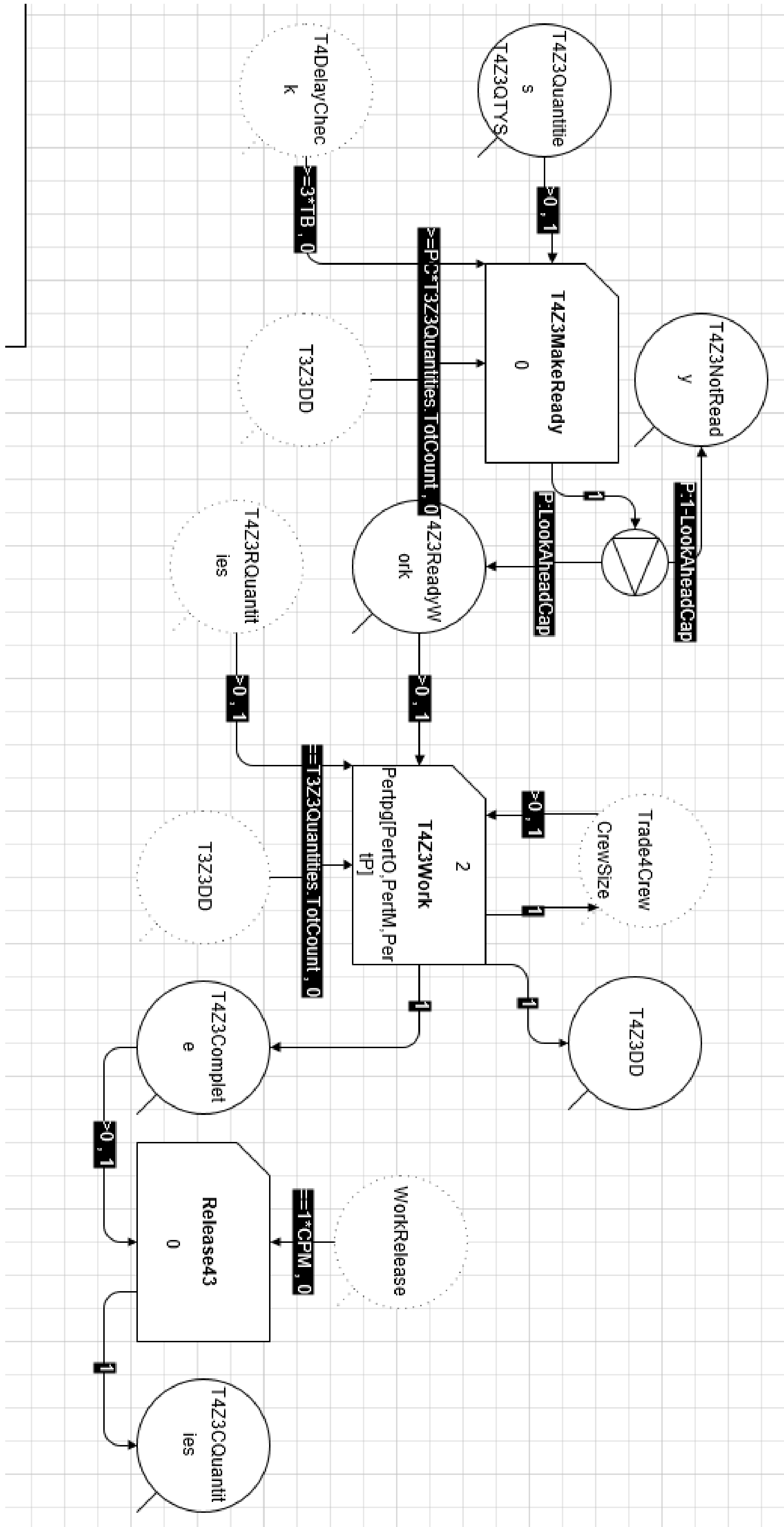


Figure 13-26 – Simulation Figure #15

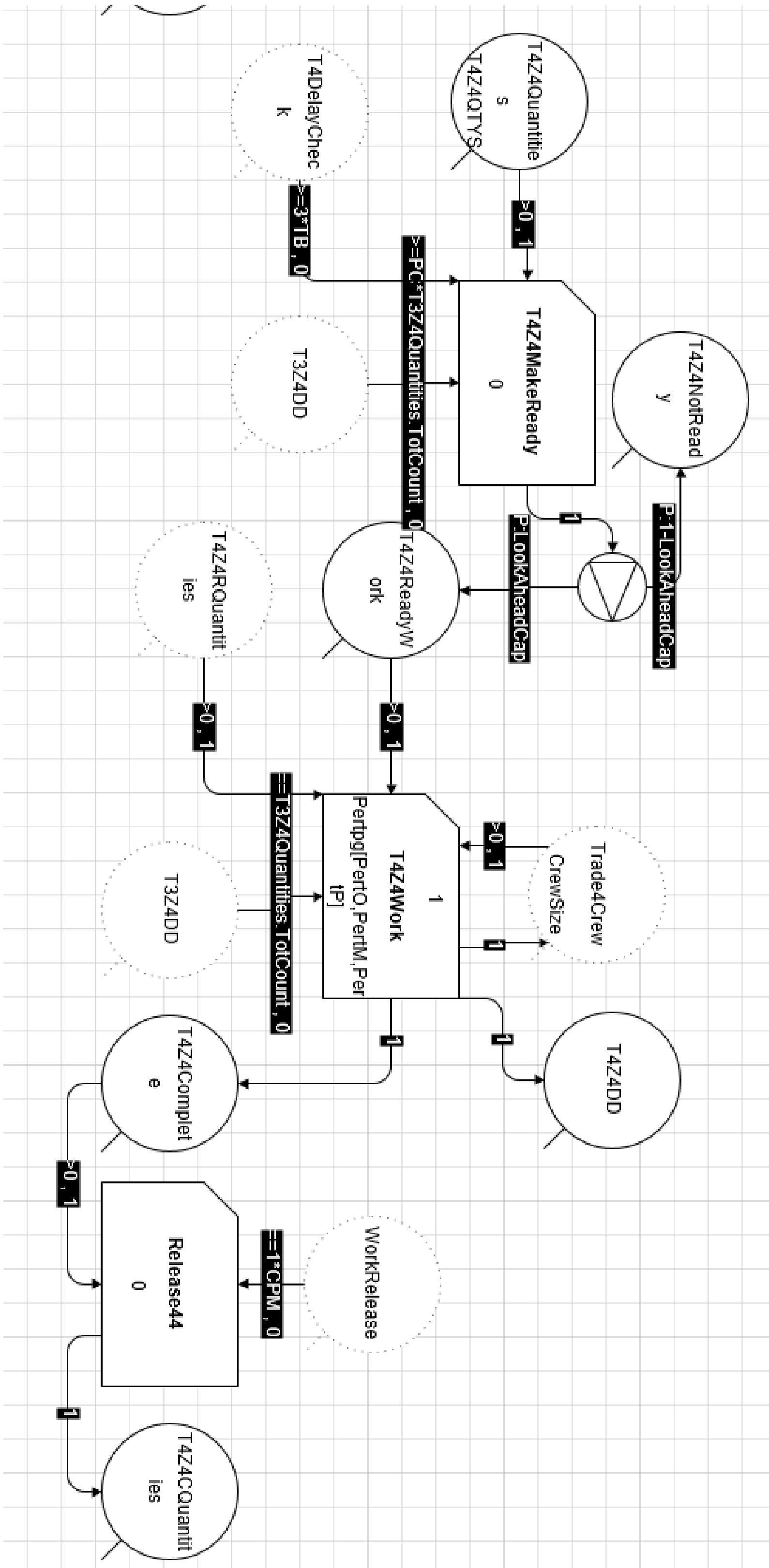


Figure 13-27 – Simulation Figure #16

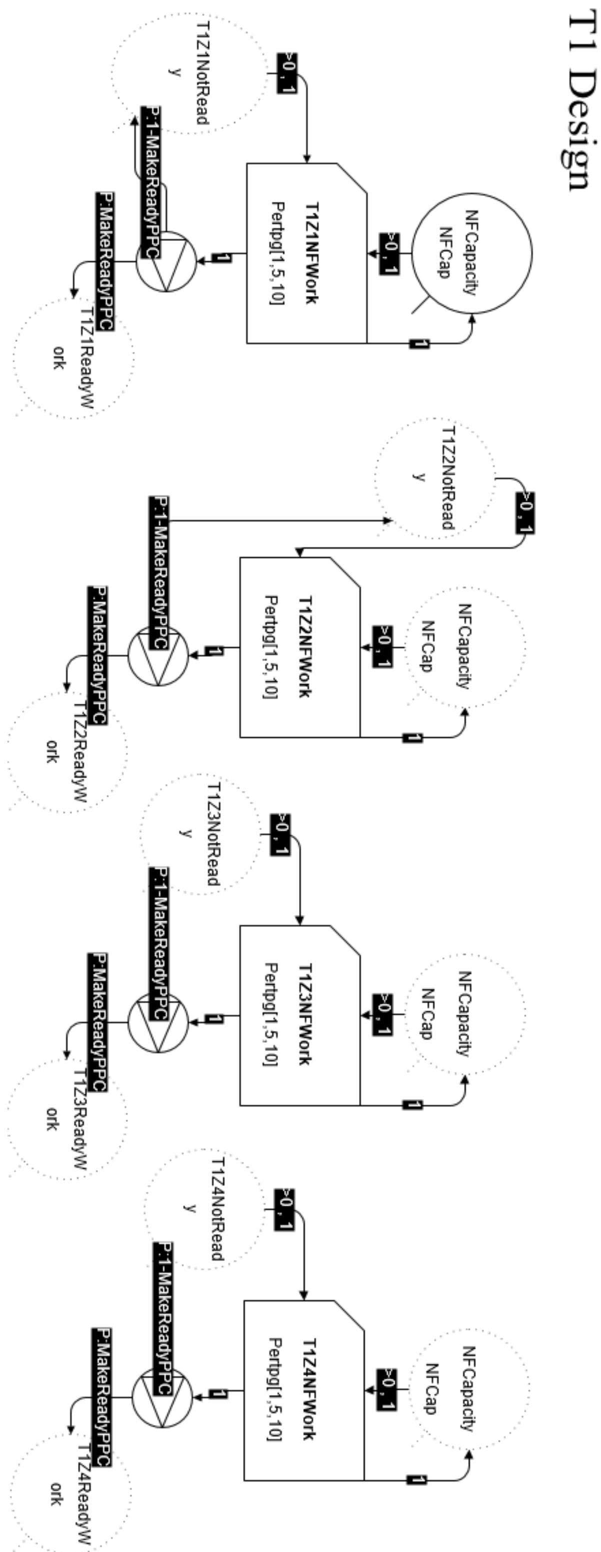


Figure 13-28 – Simulation Figure #17

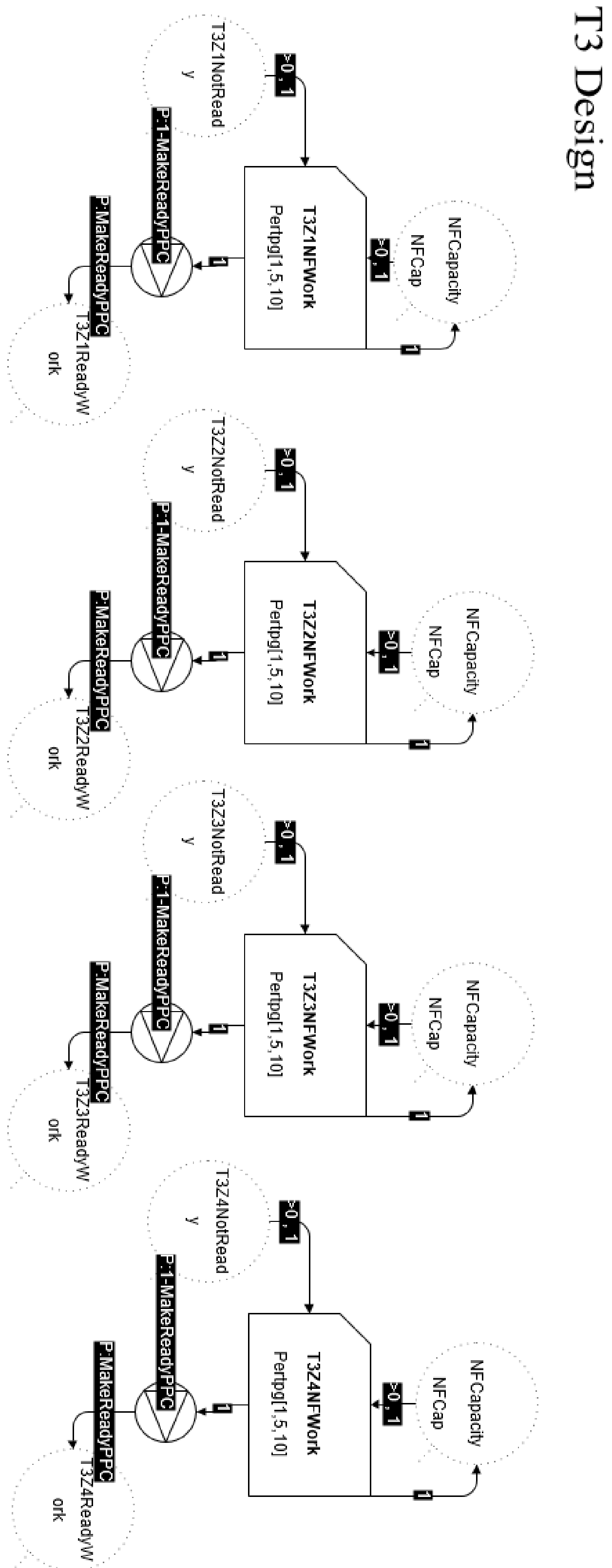


Figure 13-29 – Simulation Figure #18

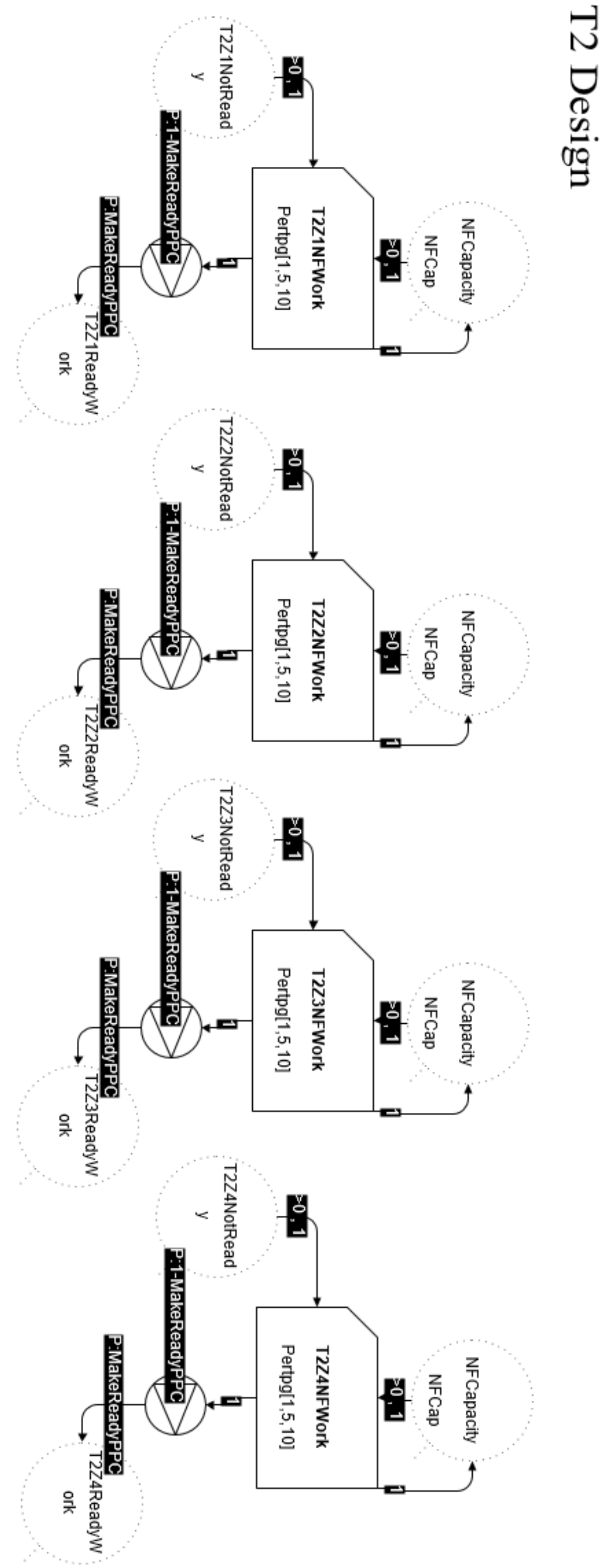


Figure 13-30 – Simulation Figure #19

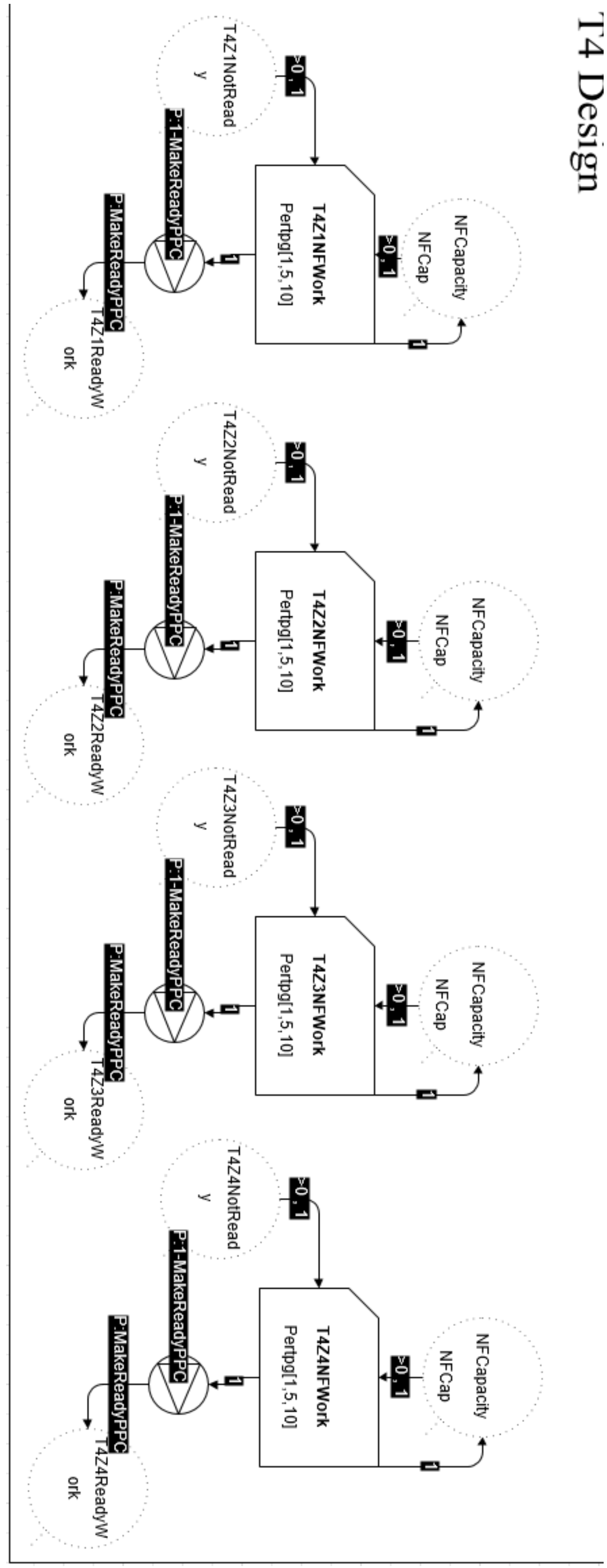


Figure 13-31 – Simulation Figure #20