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Takt planning of the fit-out of a multi-story biopharmaceutical project

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TAKT PLANNING OF THE FIT-OUT OF A MULTI-STORY BIOPHARMACEUTICAL PROJECT

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18 December 2019

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TAKT PLANNING OF THE FIT-OUT OF A MULTI-STORY BIOPHARMACEUTICAL PROJECT

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EXECUTIVE SUMMARY

This report presents a study of the development and implementation of the takt plan used to manage the fit-out of a multi-story biopharmaceutical project (the Project). The goal of the study was to capture lessons learned for all parties involved, but especially for the owner who is keen on replicating the use of takt planning and extending its scope of use on future projects.

The report starts by giving an overview of the context in which the Project unfolded. It then presents fundamental concepts and terminology pertaining to takt planning. The use of takt informs so-called "work structuring" and, when framed in the context of the Last Planner® System, applies strategically at the level of master scheduling and operationally at the level of phase scheduling. The work density method is presented to illustrate how one may go about using takt to plan a construction project.

The body of this report documents and highlights specific aspects of the development, presentation, and implementation of the takt plan that was used to deliver this Project. The data for this study was obtained by reviewing project documents, interviewing key people involved in the Project, walking the construction site at different occasions to observe work in progress, and consulting the literature.

Takt planning was used on this Project in the overhead work phase and in a different way also in the in-wall and interior finishes phase. The Project delivery team also studied options to takt the commissioning phase but did not settle on a work structure suitable to result in a functional takt plan. Takt planning of the interior finishes- and especially of the commissioning phase needs further study and experimentation on other projects.

Research findings stress the importance of using a number of project delivery practices judiciously and in combination with takt planning:

1. Commercial terms that include shared risk-and-reward incentives, so that project participants will have a stake in overall project success and fully engage in takt planning.
2. Merck's "One Team" concept, whereby the owner with all Trade Partners (on-site and off-site) meet on a regular basis to jointly steer the project in the desired direction and stay on course as the project unfolds and uncertainties manifest themselves.
3. Decoupling of phases of work, so that they can overlap in part and proceed concurrently to allow for speedy project completion.
4. Early Trade Partner involvement in project planning, particularly in the development of takt plans, so that everyone involved will have ownership in the takt planning process and be committed to the takt plan's success in execution. Effectively, Trade Partners need to:

- Help decide on takt zoning and select the takt time, based on project specifics, means and methods to use, and other project throttles.
- Forecast what crew sizes both on- and off-site they will need, and commit to providing them.
- Be transparent and honest on current progress (i.e., distinguish whether work in a takt is "done" or really "done-done").

5. Early Trade Partner engagement in design, so that construction knowledge can help to structure supply chains aligned with on-site work for accelerated delivery using takt.
6. Prefabrication to reduce on-site work density, so that the takt of certain trains (such as those involving MEP systems) can be shortened.

Lessons learned from this Project's takt plan development and implementation include:

1. The decision to takt a project must be made early in design. This is the same as for the decision to use modular construction and off-site fabrication, which also must be made early in design.
2. Those involved early-on in the project can develop a preliminary takt plan to determine feasibility of a fast project schedule (takt planning as execution strategy) and then relay and refine that takt plan with Trade Partners once they are on-boarded (takt planning as operational strategy).
3. Trade Partners brought into design can offer construction input and inform "design for takt."
4. Much of a project's repetitive as well as non-repetitive work can be scheduled with takt. Generally speaking, more work scheduled with takt is better, because of the benefits achieved with takt planning.
5. Takt times and corresponding zones will vary with the nature of the work and Trade Partners involved. Expect takt and zones to change from one project phase to the next (e.g., Overhead MEP-, In-wall-, versus Finishes phases).
6. Methods exist to date to takt component-based work (e.g., installation of unit materials and assemblies). In contrast, further study is needed on how and when to structure systems-based work (e.g., commissioning) so that it too can be planned with takt.
7. Do not expect that all work will be part of a takt train. Projects often have one-off work (e.g., MRI rooms, elevators) that due to their unique complexity is better scheduled separately and possibly without takt.
8. Takt planning is a work structuring method that goes hand-in-hand with the Last Planner® System: the work must be made ready in order to achieve high work flow reliability and on-takt performance. Do not implement one without the other.
9. In accordance with the Last Planner® System, projects should maintain a workable backlog of tasks (i.e., tasks that are not part of a takt plan) that can be done to make effective use of capacity in case work in a takted process (a "takt train") finishes early or falls through.

10. Areas not on a takt plan must be tightly coordinated (e.g., work in the corridors was coordinated on a daily basis).
11. Separate resources must be dedicated to work that is takted versus non-takted, e.g., for equipment start-up.
12. Procurement and long-lead items require their own delivery schedules. Should these not be reflected on a takt plan, they must nevertheless be synchronized with those plans.
13. Once takt trains have been established, adjusting the schedule is straightforward. Takt allows for multiple trains to run in parallel (e.g., staggering of floors as was the case on this Project) or for a train to speed-up or slow-down in order to meet the overall schedule's demand (e.g., by throttling crew sizes).
14. Buffers of time are needed in or between takt trains to articulate the time to perform "go-back work," rectify failed inspections, etc. In case of failure, process capability then also needs to be enhanced to avoid such rework.
15. Weekends and holidays (and holiday weeks) naturally offer buffering opportunities. While adding buffers means adding time to a schedule, that time allowance helps prevent reverberations through the schedule in case crews need make-up time.
16. Takt plans are visual management tools. In comparison to Gantt charts and CPM schedules, they offer significant visual benefits in getting and keeping everyone on the same page.

Recognizing that the use of takt in the construction industry is still relatively new, this report on the Project's successful implementation of takt planning should help inform and educate future project teams that wish to succeed with takting their work. It is the fine-tuning and use of the aforementioned project delivery practices in combination with takt planning that will allow for ever-faster project execution.

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1. INTRODUCTION

The purpose of this report is to detail the takt planning process that was used to manage the fit-out of a multi-story biopharmaceutical project (the "Project"). The goal is to capture lessons learned to inform the owner on how to use takt planning to deliver future projects.

The term "planning" here is used in a broad sense: it includes plan and schedule development as well as implementation and control during project execution. It includes making real-time adjustments to the plan as needed when knowledge of the project changes. To explain the practices observed, the report presents the fundamental concepts and principles of takt planning, together with anticipated benefits and challenges relative to more traditional construction planning methods.

The following section of the report offers an overview of the Project and describes the context in which it unfolded. Section 3 presents terminology, concepts, and principles pertaining to takt planning. It describes takt planning as a work structuring method. As such, takt planning augments the Last Planner® System that was developed to achieve work flow reliability but that is otherwise non-specific about how work is to be structured. At the level of master scheduling in the Last Planner® System, the use of takt will drive project execution strategy (including the alignment of the project supply chains with on-site needs). At the level of phase scheduling in the Last Planner® System, the operational use of takt planning helps to define handoffs between project participants.

Subsequently, Section 4 highlights specific aspects of the development, presentation, and implementation of the takt plan that drove the delivery of this Project. Section 5 summarizes lessons learned and challenges. Section 6 offers concluding remarks.

2. PROJECT OVERVIEW

Merck is building out a LEED Gold and WELL Building-certified multi-disciplinary facility on 213 East Grand Avenue in South San Francisco, California (Figure 1). The 9-story building with 294,000 square feet of laboratory and office space will support more than 300 scientists and staff members conducting research on exploratory biology through clinical development (Bruns 2016, Kalinoski 2016, Zaro Stahl 2018). This facility will also house a 300-seat auditorium, fitness center, café, terrace with waterfront views, and outdoor areas.

Merck typically builds its own R&D facilities, many of which are situated on the East Coast of the US and abroad, and less frequently leases properties from developers (Applegate 2018). Due to market conditions, several developer-owned and permitted properties were considered on the West Coast until Merck selected this project's location.

Figure 1: Merck Facility at 213 East Grand Avenue in South San Francisco, CA (Rendering courtesy of Alexandria Real Estate Equities, Inc. in Bruns 2016)

“Construction of biotech towers has grown since California changed its fire code about a decade ago. The higher the space, the more strenuous the requirements are for storing chemicals, for example, but the change has allowed biotech companies to look vertically for space as demand has skyrocketed” (Leuty 2019). Given the difficulty in and around South San Francisco of being able to outright purchase land to build on, leasing a building was a reasonable option.

South San Francisco is a strategic location for Merck because the Bay Area is a large life sciences hub in the State of California (e.g., Ho 2018). At present, Merck has only a small presence in the area, including one site in Palo Alto, one in Mission Bay in San Francisco, and an interim facility in leased space in South San Francisco across the street from the current project (Kalinoski 2016). Upon completion of the project, scientists will relocate and be joined by new employees to work in the new space.

On November 30, 2016, Merck reached agreement with Alexandria Real Estate Equities, Inc. on fitting out and operating the South San Francisco facility (Burns 2016). As reported, “their long-term, full-binding lease contributes to Merck’s US discovery footprint in areas where biomedical research is converging.” Alexandria had plans in place to develop this location but was waiting to identify a tenant before moving ahead with the first phase of development, namely the design and construction of the core-and-shell of their building. The agreement with Merck was reached early in that first phase so that Merck had time to offer Alexandria some input on the core-and-shell, while developing the design of its laboratory’s fit-out and then proceed with its construction.

Alexandria worked with DGA Architects to design the core-and-shell so as to deliver a “warm shell” to Merck. Alexandria then competitively bid that core-and-shell phase of the building and selected DPR Construction as the General Contractor (GC) to construct it, starting in June 2017.

A design-bid-build contract was signed, and the work was planned and delivered with traditional construction scheduling practices (i.e., not using takt).

As shown in the Project timeline (Figure 2), around January 2017 Merck initiated the process of designing and constructing their laboratory. In the remainder of this report, the Merck-specific scope of the project is referred to as the "Project" with a capital "P." Jacobs was responsible for developing the Concept Design and the Basis of Design (BOD) for the Project. They were chosen in accordance with Merck's long-standing alliance partnership with them to design their laboratory facilities worldwide. DPR Construction served on this Merck Project in the capacity of Engineer, Procurement and Construction Manager (EPCM). On-site construction of this work started in February 2018 and was scheduled to complete at a faster-than-ever speed in mid-2019.

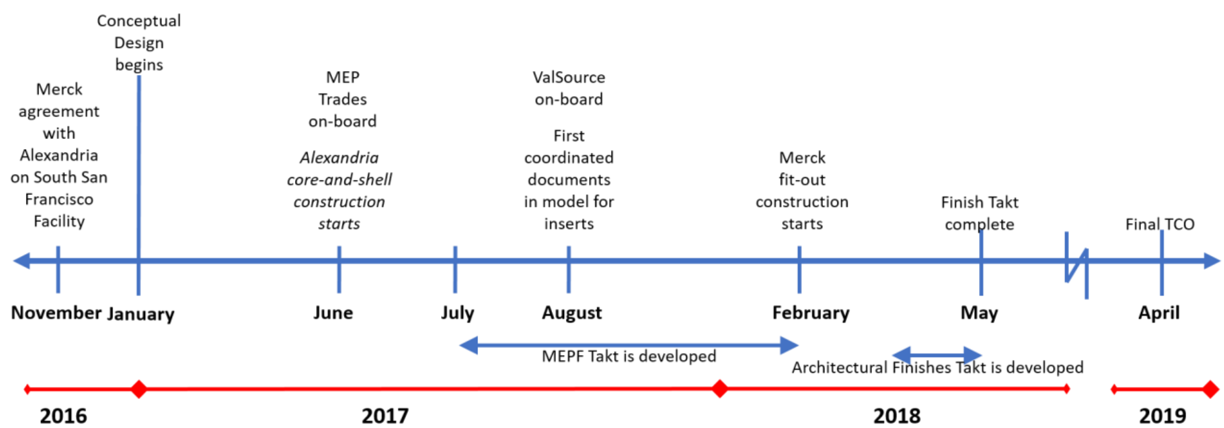

Figure 2: Project Timeline

The following section provides an introduction to takt planning concepts and terminology, and it presents a takt planning method. It distinguishes strategic- from operational takt planning. Furthermore, it describes where takt planning fits in project scheduling practice and how it relates to the Last Planner® System. Readers already familiar with these topics may move on to Section 4 of this report, that details the takt plans used on the Project.

3. TAKT PLANNING IN CONSTRUCTION

3.1. Takt Planning Concepts and Terminology

What is **takt**? Takt is German for the word beat. It is 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" (P2SL Glossary 2019).

Takt is a parameter used in designing a production system, where **production system** refers to the system used to design and make an artifact or deliver a service. When the production system is "to construct a facility," then identifying what construction work to takt, as well as setting the takt parameters for that work, is done in the course of developing the project schedule.

In contrast to a number of other scheduling methods, takt plans explicitly model space as a resource. Takt planning thus falls in the category of location-based planning methods (Frandson et al. 2015).

The goal of takt planning is to produce a production plan (a plan used to steer and control construction work on- and off-site) for a certain scope of work and with a balanced work flow.

Takt planning objectives are to:

1. Have trades work in a way they prefer, to safely deliver a quality product
2. Aim for constant crew sizes and continuous work flow
3. Avoid trade stacking (i.e., no spatial interference between trades): only 1 trade per zone for each takt (Figure 3)
4. Use timely on-takt handoffs (predictable timing of work)
5. Balance the whole while pushing for speed

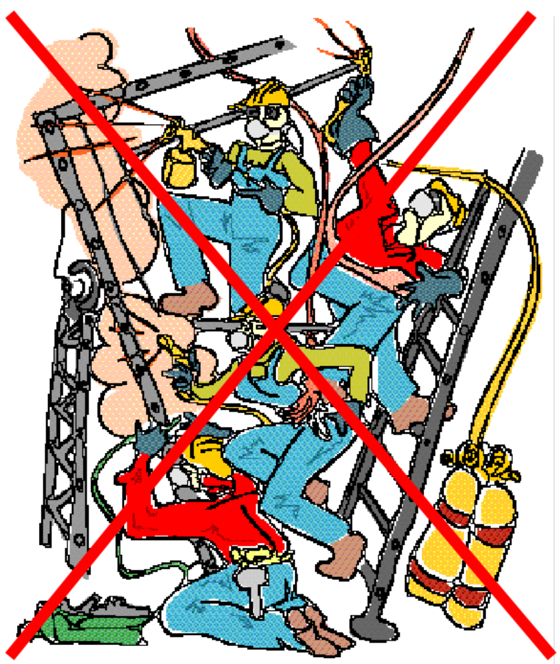

Figure 3: Takt Planning avoids Trade Stacking (Courtesy of R. Shumway)

Takt planning achieves these objectives by under-loading resources relative to their capacity. This means that resources are not booked to 100% capacity utilization but, e.g., rather to 70 or 80% or so. Consequently, when minor disturbances should require more of the resource's time, the resource will have the time to respond right away and likely be able to complete the work within the takt. Under-loading thus helps avoid reverberations in the schedule otherwise caused by one late activity impacting all its successors and possibly even the schedule end date.

Tasks in a takt plan are defined in location-specific "chunks" of work that can be completed by one Trade Partner's crew before the crew moves on to the next location. The vacated location will then get used by the follow-on crew to complete their work in the next takt, and so on, everyone progressing to the takt.

The schedule logic between tasks is defined separately for each space-type (e.g., architecturally-defined spaces such as corridors, office rooms, operation rooms, etc.) or otherwise delineated area (a **zone**) based on the amount of work to be done there by each crew that has to come through the zone to do their work. So, by space-type or zone, an **overall process analysis (OPA)** that includes tasks and dependencies is planned collaboratively, typically to inform subsequent phase planning meetings.

That scope covered in a takt plan typically spans a construction phase (e.g., overhead MEP installation, in-wall rough installation, interior finishes) or a part thereof depending on what space-types or zones occur in the phase. Specifically, it spans a period of time during which a number of Trade Partners have to perform interrelated work. A phase can therefore comprise several processes, each requiring an OPA.

Balanced refers to the desire to create a stable pace of work (matching the demand rate) for each Trade Partner, with each trade's crew proceeding through a sequence of zones (not necessarily the same sequence or the same zones for all trades).

Zones, tasks, task sequence, and takt, are all system parameters that get determined through the iterative process called **production system design**.

A key characteristic of takt planning is that each Trade Partner must complete their work in each assigned zone within a set amount of time, namely the takt. This design parameter, once set, is constant throughout the OPA. In order to accomplish reliable work completion (defined as the on-takt hand-off to the next trade), after driving out all variation that can be driven out, yet recognizing that numerous uncertainties can hamper the execution of work, takt planning uses **capacity buffers**. Trade Partners must under-load their production units (crews), that is, assign them to work at, e.g., at 70 or 80% of capacity.

One source of variation that is driven out when delineating zones is the variation in **work density**, a term coined by Tommelein in early experiments on takt planning (Dunnebier et al. 2014, Tommelein 2017a, 2017b). It is expressed as a unit of time per unit of area and defined as follows:

Given a certain work area, work density describes how much time a trade will require to do their work in that area, based on the:

1. product's design, i.e., what is in the drawings and specifications
2. scope of their work
3. given task in the schedule (depending on work already in place and work that will follow in the process)
4. means and methods the trade will use (e.g., when prefabricating off site, the work density decreases on site)
5. while accounting for crew capabilities and size.

As such, for a given Trade Partner's crew, some work areas will have a higher work density than others (e.g., compare electrical work in a lobby with work in an electrical room). Different crews will have different work densities in a given area as well (e.g., in an operating room, compare the work density of the overhead HVAC installation with that of the overhead electrical installation). Thus, through data collection, consideration given to what determines work density, and judicious design of the zones, this work density variation from zone-to-zone and trade-to-trade can be reduced, i.e., the system can be balanced.

Figure 4 illustrates this balancing act. It presents three scenarios, respectively treating the entire floor as 1 zone (A), 3 zones (A, B, and C), and 5 zones (A, B, C, D, and E). These zones are depicted by rectangles on the left-hand side of each row. The four rectangles in the middle show the grids with work densities of each of four Trade Partners' tasks in the process.

By superimposing a zoning over the grid with work densities, one can compute the amount of time each trade will take to complete their assigned task in that zone. One can then draw a histogram to show those times (right-hand side of Figure 4).

To even out the flow of work, the bottleneck task(s) must first be identified. Bottleneck tasks show up as peaks in a histogram, that is, they are the tasks that have the longest duration of all tasks in the OPA. Adjustments to the zoning or work densities may lower those peaks and make durations more even across the histogram. Rezoning may result in the bottleneck shifting from a task performed by one trade to another task performed by another trade. It may take a few iterations to rezone and redraw the histogram to find one that is deemed better. However, note that in general a 100% level workflow is just about impossible to achieve.

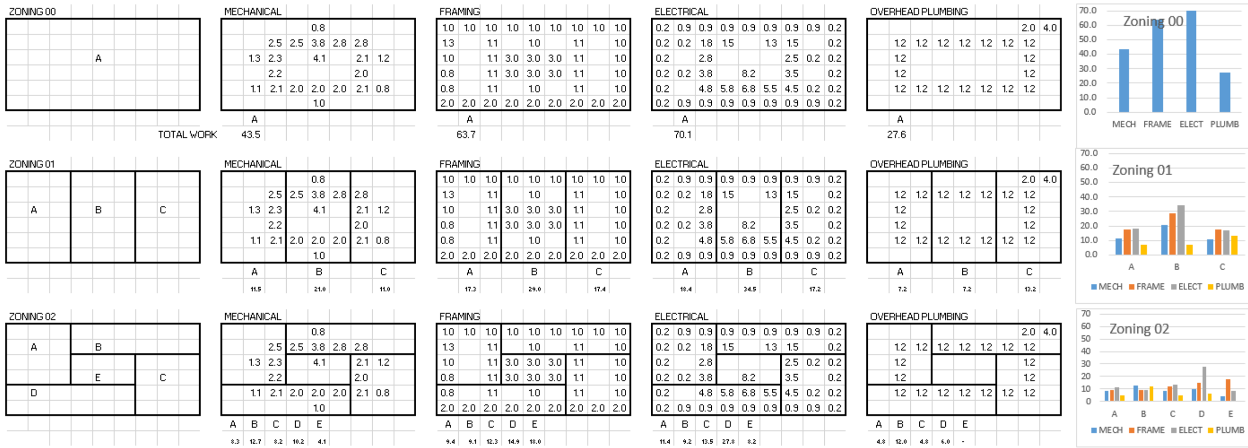

Figure 4: Work Density Method – Zoning and Balancing to Determine Takt

When for a certain zoning and given work densities the corresponding histogram is deemed sufficiently level, one then sets the takt time. Since the takt is chosen to be the time within which all tasks can reliably be completed, it will be set slightly above the peak in the histogram (see earlier mention of under-loading). Using that takt and zoning, one can then develop the takt plan by deciding on the sequencing of starts of **takt trains** (referring to a sequence of tasks in a process, connected like boxcars in a train). The planning team must ensure that the takt plan meets the master schedule requirements, or otherwise adjust the plan until it does (e.g., modify takt, change the number of takt trains, etc.)

3.2. Strategic- and Operational Takt Planning

Whether a project production system is structured using takt has an impact at multiple levels of planning. The project team's decision to use takt is both a strategic- as well as an operational one.

Strategically, takt plays a key role in defining the overall project execution strategy. Its use drives decisions about Trade Partner selection and engagement, requires supply-chain alignment, and affects the gains that may be reaped using modularization, off-site fabrication, etc. because these influence work densities. This means that the decision to takt must be made and discussed with potential Trade Partners, before selecting them.

Operationally, different takt times will set the pace for different "trains of work" in production plans. Those trains must be synchronized relative to each other so as to meet the overall project execution strategy.

3.3. Where does Takt Planning fit in Project Scheduling Practice?

Construction project schedules range from being high-level with key milestones but relatively few activity details—at this highest level, this is the so-called **master schedule**—to being low-level with many execution-specific details—so-called **production plans**. Any number of schedule levels may be needed in-between depending on the complexity of the project. Schedules at different levels get developed to serve different purposes and at different times based on project needs.

For example, the master schedule level will capture at a high level when the project is to start and end, major phases of work defined by activities (that are days-, weeks-, or even several months-long) and milestones (see When? and What? in Figure 5). This schedule is part of the contract between the owner and the general contractor, used for progress and payment tracking, etc.

In turn, at the phase level, the activities so-defined will get refined. Planners involved in the project will further explore alternative means for doing the work, and select specific means and methods to relate What? to How?

When?

MASTER SCHEDULE

What?

PHASE SCHEDULE

How?

LOOKAHEAD PLAN

WEEKLY WORK PLAN

Figure 5: Levels of Planning to Identify Work is to be Done—When? What? and How?

While the master schedule commonly gets developed at a time when Trade Partners have not yet been on-boarded and therefore cannot offer input, in general, planning efforts will benefit from directly engaging those people who will be doing the work. As Trade Partner companies and employees on-board with the project, they can participate in increasingly more detailed production planning. The planning team can leverage the expertise of these participants in defining the How? as well as confirm their ability and commitment to doing the work (respectively Can and Will in the Last Planner® System (Ballard 2000, Ballard and Tommelein 2016)). Benefits of team engagement likely will include greater buy-in and increased reliability of the plans that are developed in this way, relative to plans developed otherwise.

With "When? What? and How?" identified, the project team will then break down the work processes into more detail as the time of execution approaches. The level of detail at which to plan must reflect the facts that:

- Plans are forecasts and forecasts are always wrong.
- The further out we plan, the more wrong we are.
- The more detail we plan, the more wrong we are.

A planning system that recognizes these limitations of forecasts as well as leverages opportunities for engaging project participants personally in the planning process, is the aforementioned Last Planner® System (ibid.). This system was developed to *increase work flow reliability*, however, it is *not specific on how exactly work is to be structured*.

Assuming that takt planning is pursued strategically, it must be realized by means of operational takt planning. In the Last Planner® System, *takt planning is a work structuring method used at the phase scheduling level where handoffs between project participants get defined* (Figure 6).

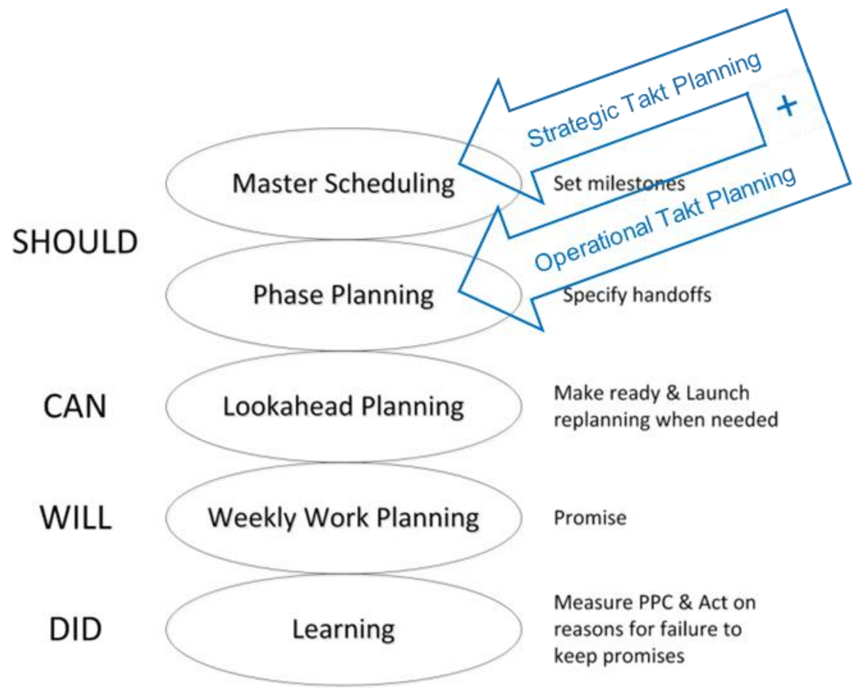

Figure 6: Strategic- and Operational Takt Planning Relative to Levels
in the Last Planner® System

3.4. Rationale for Takt Planning this Project

Takt planning is a well-established practice for structuring manufacturing systems, but its application in construction is relatively new. This notwithstanding, in recent years, a number of construction project teams have used takt planning with great success in delivering their projects (e.g., Frandson et al. 2013, Linnik et al. 2013, Brady 2014, Dunnebier et al. 2014, Binninger et al. 2016). Interest in takt planning has been sparked by Sutter Health's successful use of takt to deliver the Van Ness Geary Campus (VNGC) project in San Francisco (e.g., Berghede 2017). Recent- and ongoing industry experiments have shown that construction work planned and executed to a takt creates a *visual workplace* (e.g., Brady 2014) and yields significant benefits such as easing inter-trade coordination. The resulting increase in plan reliability and delivery quality benefits the project schedule and budget (e.g., Frandson and Tommelein 2014).

Merck insisted on using takt in order to ensure an exceptionally rapid pace in delivering this Project (Applegate 2018). Research to discover new pharmaceutical and biotechnical products cannot start soon enough and, when a discovery is made, time-to-market is crucial in these industries. Being the first to make a new scientific discovery is an advantage, but it is only the start. Managing all subsequent testing stages to obtain Regulatory Agency approvals can take a long time. It is only when those approvals have been obtained, that production can scale up and the company will start earning revenue from sales.

Merck's third-party benchmarking company IPA stated that a fit-out project of this size and complexity normally takes about 39 months (more than 3 years) to complete. By implementing takt on this Project, Merck projected building occupancy within 24 months. These 2 years spanned from the Start of Concept Design to the first area being completed, specifically from January 2017 to February 2019. That first area comprised Floors 1 through 3 and received Temporary Certificate of Occupancy (TCO) on February 11, 2019. Floors 4 through 9 received TCO on April 1, 2019. Merck received its certificate of occupancy for Floors 1 through 3 of the amenities section of the building April 29, 2019. Accordingly, the duration from concept design to first TCO was 24 months, and to final TCO was approximately 27 months. It should be noted that the takt planning process helped ensure that the TCO dates set as milestones two years prior were met on the day or within 1 or two days of plan.

3.5. Takt is the Throttle for Project Speed

Demanding increased speed from concept to delivery of capital projects is not new. It is certainly not new for Merck or other owners for whom operational opportunity costs are huge.

For example, Judy (2011) and Mayberry (2012) report on the delivery of Merck's Vaccine Bulk Manufacturing facility (VBF). Merck pushed the capital project team for ever-faster delivery times, because speed in facility design, construction, and commissioning was of utmost importance in order to build the capacity necessary to accelerate the production of much-needed vaccines.

Merck jointly with the VBF project team implemented a combination of practices that support speedy delivery, to include (Mayberry 2012):

1. The "One Team" concept, which meant organizing all project contributors (Merck, Jacobs, and Trade Partners) into an integrated partnership.
2. Co-location of the AE, CM, the owner, and other design and construction specialists in the same office space throughout the construction process, allowing for direct communication between all parties, exploration of alternatives, and timely issue resolution.
3. Decoupling the interior- from the exterior work, thereby allowing construction to be completed on both the inside and outside, simultaneously (a kind of fast-tracking). Thus, "processes that would usually be carried out in succession, such as the establishment of the basis of design (BOD) and detailed design, were instead carried out in unison at the Merck facility. This strategy saved many hours of labor, leading to an accelerated construction timeline."
4. Off-site fabrication and modular construction, which resulted in one third of the craft hours being moved off-site.
5. Lean Project Delivery, in the article (ibid.) illustrated by a description of the Continuous Quality Verification (CQV) process that engaged teams from Technical Operations and Production (supported by Maintenance, Quality, Process Engineering, Automation, Validation and/or Commissioning and Construction) in daily tier meetings to follow the project's process.

   (It is a matter of definition, but the authors of this report place items 1 through 4 in this list also under the umbrella of Lean Construction.)

In combination, these practices made it possible to build the VBF facility very fast. This poses the question: *How much faster can a project go, safely, with fewer premiums and less waste, leading to better efficiency?* Takt planning increases the project delivery speed that may be achieved by leveraging the use of these practices in combination and creating a synergy. Takt planning augments this system of practices by balancing their use in pursuit of the objective of attaining a steady work flow. Indeed, note that what the VBF team did not pursue at the time (at least: it was not mentioned in the article cited), was the drive—and correspondingly the structuring of work—to also achieve a steady flow of work.

A work flow that is steadfast and as fast-as-needed to meet customer demand is what Toyota strives for when using takt in combination with inter-related Lean methods such as built-in quality, standardization, load leveling, etc. Schmenner (1988) advocates for **swift even flow** (again, it is a matter of definition but, in the authors' view, swift even flow falls under the umbrella of Lean Construction). In the same way that troops marching to a beat can speed up or slow down efficiently—without stumbling over one another, takt serves as a throttle on the production system to speed up or slow down the pace of project delivery. A work flow that is structured and throttled in this way, will more reliably achieve the target completion dates, than can be achieved without such steadiness.

3.6. Benefits of Faster Projects (Shorter Cycle Time)

On the VBF project, use "of a hybrid modular approach cut 5 months off of the schedule and helped save $43 million in project and business spending… The team was able to cut the industry benchmark schedule down by 40 percent, accomplishing their goals in 24 months from charter to operational qualification for the $315-million, 214,000-square-foot facility. (ibid.)" These are impressive direct schedule and cost benefits achieved by faster project delivery.

In addition to direct benefits, a number of indirect benefits accrue as well. This is because, to increase speed, meticulous fine-tuning of the system is crucial. Schmenner (1988 p. 13) clarifies that "making things fast does not mean operating the fastest machines or having the most automation. It means designing and organizing the factory so that materials are always moving forward through well-maintained equipment that is easy to change over from one product to another." and "While [cycle] time reduction does not improve productivity by itself, it stimulates a host of complementary actions and tactics within the factory that, in turn, improve productivity." Speed is achieved along with good quality, low inventories, product rationalization, removal of bottlenecks, diminished chaos and confusion, reduced overhead, quick response to market, and improved capital appropriations. The benefits of reducing the cycle time of product delivery are well-recognized, not in the least by Toyota, a company that relentlessly keeps shortening their value streams. Among others, Roser (2017 p. 367) notes "One fundamental change in manufacturing within the last 20 years is the importance of speed." Likewise, construction projects stand to benefit from reduced cycle time, i.e., shorter project delivery time.

4. TAKT PLANNING OF SOUTH SAN FRANCISCO PROJECT

4.1. Commercial Terms and Selection of Project Takt Planning Team

Requiring that this Project be delivered at lightning speed (targeting the delivery to be 15 months faster than benchmark San Francisco Bay Area facilities of this type) by using takt planning, Merck entered negotiations for the tenant-improvement work with several Engineering, Procurement, and Construction Management (EPCM) firms. Merck selected DPR Construction and progressed to a Guaranteed Maximum Price (GMP) contract that included shared risks and rewards.

The DPR team selected by Merck was totally different from the DPR team that had been selected by Alexandria to construct the facility's core-and-shell. The selection of DPR for both of these scopes of inter-related construction work (core-and-shell and interior fit-out) offered the potential opportunity to fully align these two DPR teams and extensively coordinate between projects. However, this alignment did not materialize to the extent anticipated by Merck. This may be attributed to the use of two contracts each signed with a different owner and at different times, differences in commercial terms between those contracts, schedule challenges, different people being involved in each project (Project Managers, Trade Partners, etc.), and possibly other project- and contextual characteristics.

DPR and the Trade Partners it on-boarded early to tackle Merck's scope, developed a post-award construction schedule for the Project. It was a critical-path method (CPM) schedule, tens of pages long, depicted in P6 in the traditional way (one line per activity) (Applegate 2019). Such CPM schedules help to identify and manage critical-path activities, track long-lead items, etc. As is common industry practice, DPR uses P6 schedules for project controls and risk management.

Early-on, a P6 schedule's end date exceeded Merck's targeted end milestone by 4-6 months and there appeared to be lack of clarity in communication with DPR and its core team about Merck's expectation of using takt planning and when to start using it (Applegate 2019). The expectation was escalated for discussion with DPR's senior management and then resolved by DPR bringing on board personnel knowledgeable and excited about using takt planning.

The Mechanical, Electrical, and Plumbing (MEP) Trade Partners DPR had on-boarded to form the Project's core team offered crucial input in the development of the 5-day takt plan that was to meet Merck's target dates. They also had to adjust their manpower loading on-site and off-site (e.g., adding crews—a particular challenge currently in the San Francisco Bay Area, given the tight construction labor market) in order to ensure they could make the 5-day beats. The takt plan was established with the MEP trades collaboratively, under the Preconstruction/Design portion of their initial contracts. Any adjustments required to their construction costs to cover crew sizing, future planning meetings, etc. were captured within the final construction contracts which were signed after Detail Design was completed.

DPR's team for this interior fit-out Project included the following Trade Partners:

- ACCO Engineered Systems: Process piping, plumbing, and mechanical systems
- Prime Electric: Electrical systems
- Syserco: Building management systems
- WBE: Low voltage (structured cabling, security, etc.)
- Siemens: Fire alarm
- COSCO: Fire protection
- DPR: Framing and drywall
- Casework
- Laboratory equipment
- Flooring

- Trade partners for other finishes
- Valsource: Commissioning

DPR opted in its subcontract agreements to offer shared risk-and-reward incentives to key Trade Partners. This is an approach the company commonly uses as a means to foster collaboration and increase the likelihood of project success. Such incentives help to align the interests of Trade Partners as they develop and subsequently execute their takt plans.

4.2. Description of Overall Takt Plan

DPR brought in Adam Frandson to coach the takt plan development effort. Adam had studied Lean Construction and wrote his doctoral dissertation in Engineering and Project Management at UC Berkeley on takt planning (Frandson 2019a), so he had expertise to bring to bear. Jointly with DPR Project Management staff including Superintendent John Eberhard and Trade Partners for the MEP overhead phase, the team decided during early coordination meetings how to zone the floors and develop a takt plan starting with that phase. The work zones were established taking into account the number of prefabricated assemblies to be installed. Critical components discussed when creating work zones were metal framing, heating, ventilation, and air conditioning (HVAC), and pipe racks, because they required coordination to avoid undue impact on one another (e.g., metal framing impacted electrical rough-in while prefabricated pipe racks affected plumbing). Work zones were kept spacious: they had to be large enough to accommodate large prefabricated assemblies (e.g., plumbing carriers). Their adequacy was confirmed using layout and logistics plans.

Deliveries especially for long-lead prefabricated items were not shown on the takt plan. Instead, DPR used a separate loading calendar and reflected deliveries in their P6 schedule. Each Trade Partner had an assigned day of the week for material deliveries. These dates could be reflected on the takt plan, in future projects.

The team established a 5-day takt. Considering that the majority of Trade Partners had 5-day work weeks, a 5-day cycle allows for easy assessment of work completed each Friday. Moreover, evening shifts and/or weekends then provide buffer time for trades to go back to any work not completed within their takt without impacting the next takt cycle. The agreement was that any trade not completing their work within their takt, would make up for it that same week on Saturday. A trade would not get compensated for such overtime unless the go-back work was due to other trades or schedule changes (i.e., outside of their control).

The method the Project team used to the develop their takt plan included 5 steps, repeated as needed to find the takt suitable for each process in a given phase. Figure 7 (upper left) shows these steps, namely: (1) collecting data for planning, (2) defining zones and work in those zones, (3) rough balancing, (4) reaching team agreements, and (5) fine balancing the takt plan (after Ballard and Tommelein 1998, Frandson and Tommelein 2014). These steps essentially align with the steps of the work density method described previously, though the Project team likely did not consider work densities at the level of detail illustrated in Figure 4.

Figure 7: Overview of Project Management Systems (Gadbois et al. 2018)

Figure 7 (lower left) illustrates the takt zones the team identified. While work at ground level was one-of-a-kind, given unique spaces such as the lobby area, auditorium, etc. (Figure 8), the tower itself was more repetitive from one floor to the next (Figure 9). Figure 7 (upper right) illustrates how the Project's Building Information Model (BIM) informed the team on where the work of overhead MEP trades was located on the floor. Figure 7 (lower right) depicts one of the weekly Trade Partner coordination meetings during which the takt plan was reviewed and progress assessed.

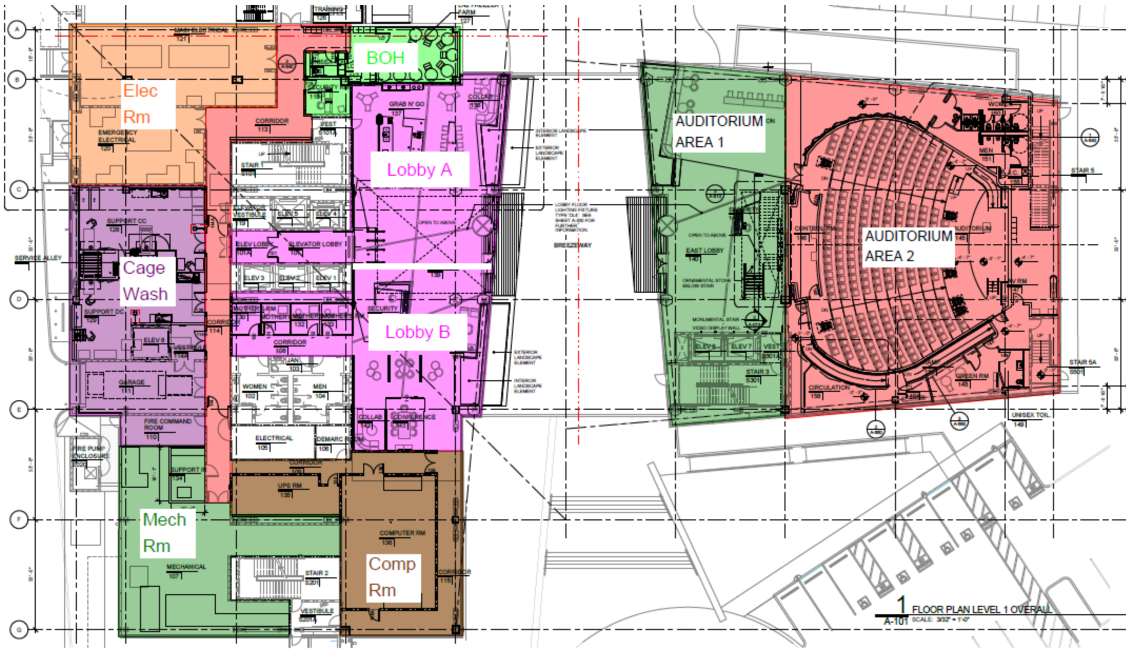

Figure 8: Zoning of Ground Level (Courtesy of Merck)

Figure 9: Floor Plan Level 2 (left) and Level 3 (right) (Courtesy of Merck)

To give an idea what area might make up a zone, consider the floor plan of Level 3 shown in Figure 9. The four zones (each shown in a different color) are takted to a 1-week beat (5 work days) and include the brown Area 1 of about 3,100 ft^2 (~300 m^2), magenta Area 2 of about 2,700 ft^2

(~260 m^2), green Area 3 of about 4,700 ft^2 (~450 m^2), and blue Area 4 of about 5,300 ft^2 (~500 m^2). Depending on the phase of construction the work is in, zones may be delimited by architectural features such as walls and columns. However, using such product features to delimit zones is not necessarily the best way to proceed when developing a takt plan (e.g., early on in the project, walls do not yet exist).

Figure 10 illustrates the overall takt plan of this Project, documented using Microsoft Excel. It shows the work structured by zone in the first two columns (vertical axis) and it shows time on the horizontal axis. Note that this plan as of 6 June 2018, remained essentially the same through Project completion. Also note that all activities that are captured here on a single page, would have taken many pages to show on a CPM schedule.

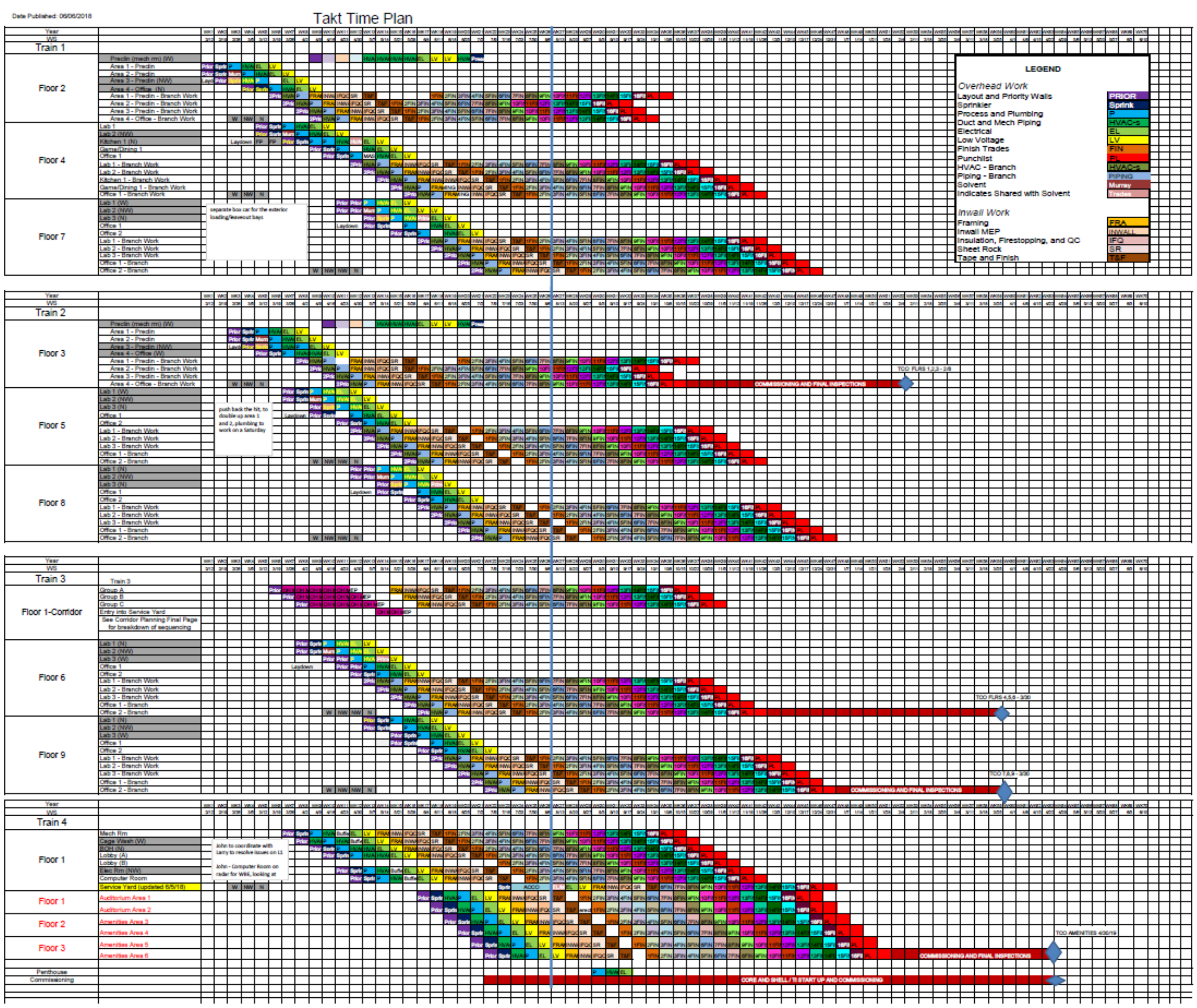

Figure 10:.Overall Takt Plan (Date Published: 06/06/2018)

The takt plan is organized in four sections, called “trains” by DPR, each with processes (one process per row, and each column one week in duration) that have staggered starts in order to balance workload. The speed of the work in the overall takt plan was determined by taking into account technical feasibility and the demand for speed by Merck. The Project team estimated that 16-weeks was the shortest achievable duration to fit out the space (Frandson 2019b) (this is the duration, e.g., starting with the first purple Prior boxcar on Floor 2 to the last to the last brown T&F boxcar on Floor 2). A 16-week duration therefore paced the work throughout.

The legend of the plan shown in Figure 10, enlarged in Figure 11, shows the colors assigned to each trade. Such color-coding greatly enhances the readability of the plan and helps support visual management (e.g., Brady 2014).

DPR assigned one superintendent per train so that they could run multiple trains in parallel and accordingly shorten the project delivery time (e.g., the work on Floor 3 in Train 2 starts two weeks after the work on Floor 2 in Train 1). Each train has boxcars (one per cell), with each boxcar referring to a week’s worth of work. Each train (column 1 in Figure 10) is further broken down by floor and then by zone on those floors.

LEGEND	
Overhead Work	
Layout and Priority Walls	PRIOR
Sprinkler	Sprink
Process and Plumbing	P
Duct and Mech Piping	HVAC-s
Electrical	EL
Low Voltage	LV
Finish Trades	FIN
Punchlist	PL
HVAC - Branch	HVAC-s
Piping - Branch	PIPING
Solvent	Murray
Indicates Shared with Solvent	Trades
Inwall Work	
Framing	FRA
Inwall MEP	INWALL
Insulation, Firestopping, and QC	IFQ
Sheet Rock	SR
Tape and Finish	T&F

Figure 11: Colors Assigned by Trade-specific Process Step
(Legend of Takt Plan in Figure 10)

- Train 1 includes Floor 2, Floor 4, and Floor 7.
- Train 2 includes Floor 3, Floor 5, and Floor 8.
- Train 3 includes Floor 1-Corridor, Floor 6, and Floor 9.
- Train 4 includes Floor 1 (various zones), Floor 1 (auditorium), Floor 2 (amenities), Floor 3 (amenities), and Penthouse.
- The work pertaining to the process of Commissioning and Final Inspections is shown by a red bar, ranging from 12- to 16-weeks long, and ending at a TCO milestone. The TCO for Floors 1, 2, and 3 (combined) had an earlier date than the TCO for Floors 4 through 9. The Amenities had a separate process of Commissioning and Final Inspections and an even later TCO date.

The reason for splitting the trains as they were, was to stagger the start of work so as to deliver each floor in a logical progression. Merck and DPR recognized that if you have one crew per train and the trains are split in numerical order by grouping Floors 1, 2, 3, then 4, 5, 6, and 7, 8, 9, construction would be completed in order 1, 4, 7, 2, 5, 8, 3, 6, 9. By breaking up the trains as shown, three separate crews can start working on Floors 1, 2, 3 at more-or-less the same time and the completion of that work will be closer in time than would be the case with one crew working through Floors 1, 2, 3 sequentially. This is beneficial to starting Commissioning and Final Inspections.

Within each floor, the tasks are distributed amongst work zones. A number of design features are repeated. Besides Floor 1 and the auditorium, Floors 2 through 9 all consist of laboratories and office spaces. Figure 9 illustrates that the work zone breakdowns on floors 2 and 3 are nearly the same. The same pattern applies when the floor layout changes in minor ways on the higher floors.

4.3. Details of Takt Plan for Overhead Phase

Figure 12 zooms in on four rows in the overall takt plan (Excerpt from Figure 10), each one detailing the process steps (colored by trade, according to the legend shown in Figure 11) that are included in the Overall Process Analysis (OPA) (or, in other words, in the sequence of trade construction) for that zone. The OPA varies slightly from one row to the next due to architectural differences but, clearly, planning effort has gone into avoiding trade stacking and allowing trade crews to “flow” from one zone to another (e.g., EL spends 5 days working in the zone corresponding to row 1, then 5 days in the zone corresponding to row 2, and so on).

Prior	Sprin	P	HVA	EL	LV			
Prior	Sprin	Murr	P	HVA	EL	LV		
Layd	Prior	Sprin	HVA	P	.	EL	LV	
			Prior	Sprin	P	HVA	EL	LV

Figure 12: Four Sequences (one per row) of Process Steps, Each One the Result of an Overall Process Analysis in the Overhead Work Phase (Excerpt from Figure 10)

Figure 13 elaborates on the six boxcars that follow one-another, as depicted in the first row of Figure 12. The first column in Figure 13 depicts the boxcar in its designated color, matching the color in Figure 12 of the corresponding cell in the takt plan in Excel. To the right are details of the work to be done and handoffs to be achieved in the 5-day takt. The second column's header mentions "Company" and for each boxcar should have included the name of the Trade Partner(s) involved (e.g., Priority Walls was DPR Drywall, Sprinkler was Cosco Fire Protection, Piping was ACCO, HVAC was ACCO and Therma, Electrical was Prime Electric, and Low Voltage was Syserco, Prime Electric, or Siemens depending on the specifics).

Of note in the third column is that "Clean up and leave it like you found it" appears in each boxcar: it is requisite for a clean handoff to the trade that comes to work in that zone in the next takt. In the Sprinkler boxcar, reference to "Murray sharing takt in specified locations" indicates that coordination and some sharing of space with another trade is expected within the designated takt. This may or may not be considered trade stacking, depending on how large the shared zone is.

Figure 14 zooms out again to highlight a "natural" buffer week in the plan (cells that are left white) created by a holiday (red vertical line) and created as a result of work contents and staggering of trades. Taking a single day (such as a holiday) off the schedule would have created havoc in the 5-day week-beat schedule. Therefore, the team decided to not schedule any new work that entire week but, instead, afford themselves this time to catch up on work that fell behind (e.g., go-back work). The blue arrow delineates a natural buffer created prior to the "1 Finishes" hand-off. The empty cell allows for the preceding trades, such as tape and finish, to complete go-back work if necessary.

The inclusion of such buffers in the schedule is contrary to traditional scheduling practices where work is required to start as soon as it possibly can. However, the benefits of strategically adding buffers far outweigh the "perceived time loss."

Updated 10/10/2019		TAKT PLAN HAND OFF DESCRIPTIONS
Takt / Week	Company	Activity **Clean up at each box car includes getting debris to the loading bay and then the single dumpster**
PRIORITY WALLS 1		Vertical soffit attachments at a minimum, soffit framing
		Priority full ht. walls
		Column wraps
		Layout
		Loading day for drywall Tuesday
		Above ceiling drywall - one side, then close up inspection, then other side
		Fire tapping - head of wall
		Clean up and leave it like you found it
	NOTES	
SPRINKLER 2		Remove and reinstall mains and branch lines as necessary
		Install hangers
		Install seismics
		Fill with city water as a precaution
		Load floor on Thursday
		Clean up and leave it like you found it
		Move material out of area
		Murray sharing takt in specified locations
	Service Yard:	Set up boiler pads and remaining equipment yard pads
	NOTES	
PIPING 3		Stocking on Fridays
		install all hangers
		install modular racks
		making connections for modular racks
		testing for supply
		install seismic connections
		Insulate piping and label
		Clean up and leave it like you found it
		Connections to riser mains
		Fire stopping as available
		Valve Tags
		Insullation and Labels
	Service Yard:	Pour boiler skid pads and remaining service yard pad
	NOTES	
HVAC 4		Load in on Mondays
		Modular exhaust mains
		Modular supply mains
		FSD that are inline with mains
		inspections
		duct leakage inspections - 25% of High perrssure mains, 5% of balance
		Ensure duct ends are bagged or covered (LEED)
		Propress heating hot water and chilled water mains
		Clean up and leave it like you found it
		Install Seismic
		Insulation and labels
		Firestopping as available
	Service Yard:	MAS Metals Stairs/Rails/Grates
	2 wks of HVAC	Rig boilers and steam generators into place and boiler connections
	NOTES	
ELECTRICAL 5		
		Install prefabbed hangers, racks, seismics
		Install conduit, including branch
		All loading per loading schedule
		Clean up and leave it like you found it
		Tie in to electrical in priority walls
	Service Yard:	MAS Metals Stairs/Rails/Grates
	2 wks of Elec	Continue Boiler and Steam Generator connections
	Notes	inwall electrical are getting prefabbed
LOW VOLTAGE 6		Conduit by Prime and Syserco
		Rated Wall Sleeves - WBE, Syserco, Prime
		Seismic
	Service Yard:	Continue Boiler and Steam Generator connections
	NOTES	

Figure 13: Boxcar Details of Overhead MEP Overall Process Analysis

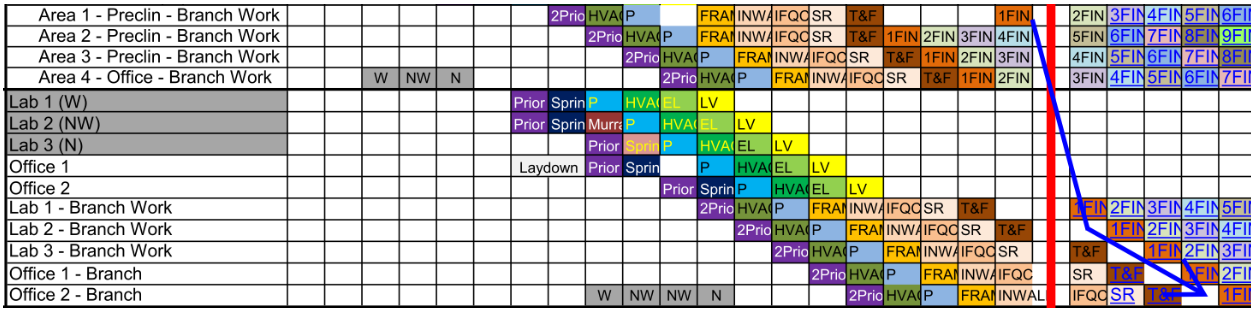

Figure 14: Natural Takt Buffer Prior to Finishes OPA

Team members stated that incorporating more natural buffers can be beneficial on future projects. Starting from late March 2018, Trade Partners have worked every Saturday in addition to swing shifts throughout the week. Having to work outside of normal hours, go-back work has to be paid for by the responsible parties and demands increased coordination. For future projects, the project team recognized that using weeks consisting of holidays helps to mitigate go-back work. Because of the uneven distribution of holidays over the course of a calendar year, additional opportune times must be identified to insert such buffers in the takt plan.

4.4. Prefabrication as a Means to Reduce Work Density and Takt

Merck set a goal for this Project to get 50% of the typical field man-hours (which does not include management and design-type man-hours) off site by way of prefabrication. They set this goal for both safety and productivity reasons.

The Project achieved and average of 30% total field man-hours off site or approximately 100,000 hours off site. The bolus of those man-hours were for the Piping and HVAC trades, which achieved a very high productivity and safety performance. More specifically, during MEP overhead installation, 50% of all project hours were off-site shop hours. A lot of high work and hot work for piping and HVAC was removed from the site.

If you estimate that shop hours are approximately 30% more productive, without the off-site hours the Project would have had to manage and additional 130,000 man-hours (approximately 65 craft workers working 2,000 hours/year for a full year) on site to accomplish the same work.

Off-site fabrication no matter how small will almost always benefit the project from the schedule productivity- and most importantly from the safety perspective. Merck's expectation on future projects is to continue to strive to move more and more work off-site and make the actual construction more of an assembly process that is very safe and efficient for all parties.

Figures 15 and 16 respectively illustrate the use of prefabricated walls and prefabricated pipe racks.

Trade Partners were aware of Merck's prefabrication expectations and credit their corresponding efforts to meet these expectations towards the success of the takt plan implementation (Mirkovich 2018). A high degree of prefabrication enabled the DPR Project team to meet the established 5-day takt.

Figure 15: Prefabricated Wall

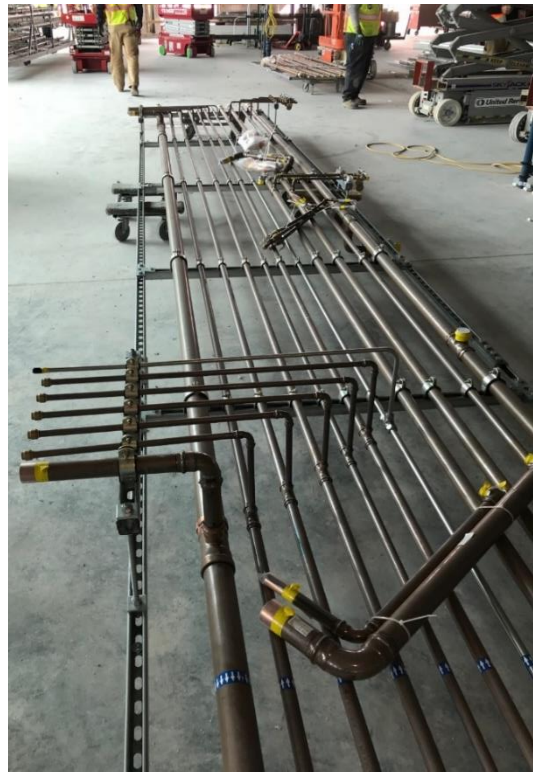

Figure 16: Prefabricated Pipe Rack

Prefabrication is a well-known construction management approach that can increase project delivery speed as well as project performance in terms of quality, safety, and possibly also cost. In particular, project delivery time savings stem from (1) the reduction in the amount of time needed for on-site work and (2) various parts of off-site work possibly being performed concurrently with one another.

In regards to takt planning, of note is that the use of prefabrication reduces the time the trade will need to do their on-site work in certain areas, that is, it reduces that trade's work density. If that trade has work that is the bottleneck in the process, then the project management team can strategically invest in prefabrication of work related to that trade in an effort to lower the takt. The corresponding process will then progress faster; how much faster is constrained by what will emerge as the next bottleneck in the system. An analysis of work density can thus inform where and what to prefabricate. For this reason, prefabrication is part of any takt planning execution strategy. It requires strategic decision-making and commitment so that all related supply chains can and will be aligned, and it demands increased focus on logistics and access because components brought in tend to be physically large.

The selection of alternative means and methods for this Project also reduced work density, benefitting the takt planning process as described in the previous paragraph. An example is the use of crimping (on this Project using ProPress®) instead of welding of pipe connections. Crimping made this work go faster and in addition also removed related work from the schedule, such as getting permits for hot work.

4.5. Details of Takt Plan for Finishes Phase

Figure 17 zooms in on five rows in the overall takt plan, each one detailing the process steps (colored by certain work to be done in a certain week) that were part of the Finishes OPA for the corresponding zone. Figure 18 elaborates on the first two boxcars 1FIN and 2FIN depicted in Figure 17. Each boxcar details the work to be done and handoffs to be achieved within the 5-day takt.

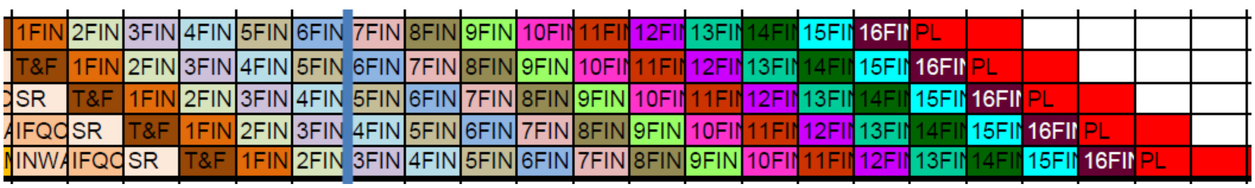

Figure 17: OPA for In-wall and Finishes Phase (Excerpt from Figure 10)

It appears that, when choosing the takt for the finishes phase, the Trade Partners decided to maintain the zoning and 5-day takt that had governed the Overhead MEP takt plan. These zones are relatively large. Trade Partners involved in the finishes are shown working side-by-side in each boxcar each week, sharing the zone and coordinating its space use among themselves. As mentioned, whether this resulted in trade stacking depends on how large the shared zone is and what work is to be done where. Even if some trade stacking occurred it may have been found acceptable by those involved, whereas it was avoided to a much greater degree in the Overhead MEP takt plan. Another work structure making use of smaller zones would likely have made the load balancing harder to accomplish because variability increases relatively speaking when using smaller zones. In contrast, larger zones afford the opportunity of pooling workloads.

The details of the takt train for the finishes OPA (column 2 in Figure 18) reveal that a different rationale applied when crafting the work structure to suit the desire to maintain the zoning and takt specifics of the Overhead MEP phase. Whereas the second column in Figure 13 would have listed the single Trade Partner in charge of the boxcar (e.g., “DPR Drywall” for the Priority Walls boxcar and “ACCO” for the Piping boxcar), the second column in Figure 18 lists a multitude of zones where work will take place in the 5-day work week. It is a takt plan of a different nature when compared to the Overhead MEP takt plan.

FINISH TAKTS		
1 FINISHES (15)	Vivarium	Prime and First Coat, and Spray Door Frames (R, F)
		Install cable tray and associated hangers
		Build MRI Shield (wk 2/2)
	Offices, Bathrooms, Game&Dining, Lobby, Amenities	Prime and First Coat (R, F)
		Blackout painting above ceiling (R, F)
		Pull Wire - All Plenum rated cable (M, T, W)
		(Amenities Area 1) - Prep for River Rock
		(Amenities Area 1) - Landscape Wall complete
		(Amenities Area 1) - Coring for Handrails at the Ramp
		Install cable tray and associated hangers
	Labs	Prime and First Coat (R, F)
		Install cable tray and associated hangers
	Kitchen & Servery	Install cable tray and associated hangers
	Auditorium	Install Ceiling support system
		Install cable tray and associated hangers
	Service Yard	XXXXXXX
		XXXXXXX
		XXXXXXX
2 FINISHES (16)	Vivarium	Epoxy Floors, Walls (Grid Ceilings) (wk 1/2)
		Epoxy Floors, Walls, Ceiligns (Hard Lid Ceilings) (wk 1/2)
		MRI Flooring (wk 1/2)
	Offices, Bathrooms, Game&Dining, Lobby	Terrazzo (wk 1/2)
		Floor Seal (wk 1/2) - Swing
		Ceramic Tile (wk 1/2)
	Labs	Floor Seal (wk 1/2)
		Nora Flooring (wk 1/2)
	Kitchen & Servery	Set hoods (wk 1/2)
	Auditorium	Install Acustical Treatment
	Service Yard	XXXXXXX
		XXXXXXX
		XXXXXXX

Figure 18: Takt Train Details of Finishes Phase

Simplicity certainly is a benefit of maintaining the zoning and takt across phases. Zones people can speak to and follow, helps with project delivery (Frandson 2019b). For production purposes, however, given that the work of finish trades has rather different workflow characteristics than Overhead MEP work, instead the Trade Partners could have revisited the work structure and established a different zoning and takt for the processes in this phase. Generally speaking, since the commercial terms for engaging (finish) trades, the timing of their on-boarding with the Project, and the trades' alignment with their supply chains must all be considered when developing a takt plan for any single phase of work, most likely this will result in a plan with a zoning and a takt different from those developed for other Project phases.

4.6. Consideration of Using Takt in the Commissioning Phase

Recognizing the importance of commissioning especially in light of the complexity and speed of the Project, Merck on-boarded their commissioning agent early, in August 2017 (late would be when all systems are fully installed). The scope of work of the commissioning agent is to review drawings and ensure everything is installed per the design. Given the team's use of takt planning, a practice that was new to the commissioning agent, their traditional commissioning methods had to be adjusted. The commissioning agent found that the takt plan was easier for them to interpret in comparison to a P6 schedule, especially given the high level of complexity of this Project (Andrews and Colon 2019). Use of takt meant that systems in each zone might not be mechanically complete at the time of inspection. Systems tended to physically span across multiple takt zones. The commissioning agent therefore conducted "walk-downs" (as opposed to testing) by zone within each 5-day takt, a process more time consuming than would otherwise be the case but it also gave them a head-start on creating punch lists and thus ensuring quality early-on. Full system testing was then scheduled for a later date.

Extensive use of prefabrication had a large impact on the commissioning process. Traditionally, each commissioning agent would be responsible for a component of the MEPF systems: one for gasses, another one for plumbing, chilled water, hot water, etc. Since on this Project all these systems were installed in prefabricated racks, agents had to simultaneously walk-down multiple systems. Defects such as pipe on racks labeled or connected wrong, could be noted sooner. Thanks to earlier inspections, the agents also noted that pipe racks installed first would be covered by HVAC duct and thus become inaccessible for testing and repair. They highlighted this to DPR and the issue was resolved before HVAC was installed across all floors (Andrews and Colon 2019).

Not unlike other projects, obtaining documentation—a requisite input to commissioning—was difficult on this Project as well. The volume of documentation needed was large due to the complex nature of the work. The commissioning agent had to search through the Building Information Model (BIM) and shop drawings, and felt that the BIM as-built updates were not timely enough (Andrews and Colon 2019). The shop drawings were not the final as-builts they had liked to have in hand during their walk-downs.

The commissioning agent noted that, having been on-boarded early during the BOD development by Jacobs, the design could have been more thoughtful of the takt planning, pre-fabrication, and commissioning needs. For example, the designer could have done a better job of ensuring that all equipment called out on the designs were approved by Merck and of keeping constructability in mind.

The commissioning agent had not been involved upfront in defining takt zones. In future projects they certainly should be involved in developing boxcars, setting up the boxcar requirements for each trade, and listing documentation requirements and punch-list correction requirements.

The Project delivery team made several attempts at using takt for all scope in the commissioning phase but despite extensive study of alternatives, no suitable work structure was identified to that effect. Figure 19 illustrates that Commissioning and Final Inspections added-on to the end of a takt train. Figure 20 illustrates the plan to start up equipment, which has to be aligned with the completion of the requisite construction work.

Figure 19: Commissioning and Final Inspections Task Spanning Multiple Takts (Excerpt from Figure 10)

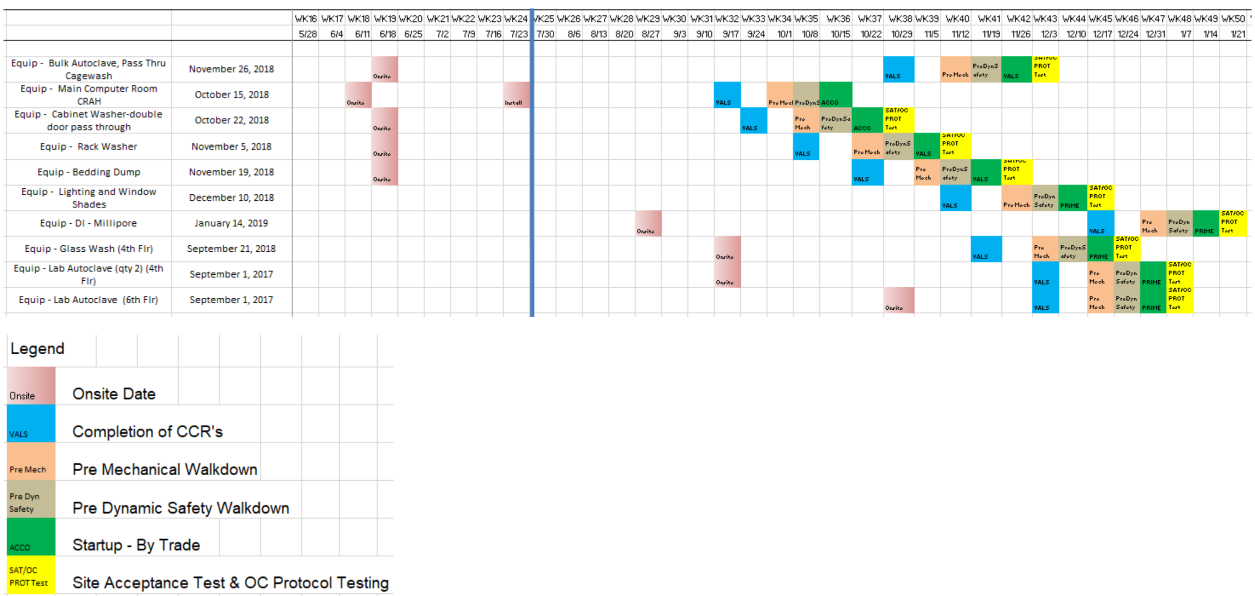

Figure 20: Commissioning Plan for Equipment Start-up

The systems-based nature of commissioning, as opposed to the construction component- and assembly-based nature of installation work in earlier construction phases, requires (again, as was the case for the finishes phase as compared to the overhead MEP phase) different work structuring to suitably define, not only the spatial distribution of work in the process and hand-offs in-between process steps, but also the completion of construction work that defines when the Commissioning and Final Inspections process can start.

Takt planning of the commissioning phase needs further study and experimentation on future projects. This will be well-worth figuring out. A commissioning plan structured within takt will pull the completion of preceding takt trains, all of which need to be aligned so that greater project delivery speed and predictability can be achieved. This will provide a clearer picture of the "total" project actual completion forecast, not just the construction phase's.

4.7. Production Tracking Based on the Takt Plan

Successful execution of a takt plan demands that every Trade Partner reliably makes their hand offs (meaning they complete their work within the takt time), thus it is critical to control the schedule as the work progresses within the takt in order to gauge if the hand off will likely or not occur as planned. Because a takt is only is a few days long (5 days on this Project) this creates a sense of urgency (Frandson et al. 2013). Visually communicating both performance and the plan to everyone is an important part to distributing control, identifying deviations, and maintaining the schedule.

Should a takt be missed by a trade, then the remaining work for that takt may be completed immediately with overtime, completed during the following takt provided it doesn't interfere with the succeeding trade, or be done later perhaps (e.g., using a weekend- or a holiday buffer as shown in Figure 14). A takt plan clearly shows which trade would be impacted, so it makes coordination between succeeding trades easy. Much depends on the work structure, whether the incomplete work is unique to that particular zone (e.g., missing design details), and whether any follow-on trade's work depends on it. The reason for the miss should be immediately researched and a countermeasure developed so as to avoid repeatedly impacting future tasks. The benefit of using takt in this way is that problems are identified and corrected quickly, instead of passing that production variation to the succeeding tasks and potentially rippling through the schedule. However, in extreme cases, the entire takt train may have to come to a halt and restart only at a later time depending on the reason for the miss.

Figure 21 illustrates the control dashboard that DPR maintained to report on Project progress at Owner-Architect-Contractor (OAC) meetings. This dashboard displays DPR's data that tracks whether Trade Partners met their commitments in the 5-day takt control cycle. Figure 22 shows a part of the overall takt plan, each cell now filled out with a number (replacing the boxcar label) that assesses the percentage of completion of the corresponding Trade Partner's work in that takt. Values range from 0 to 1, where 1 marks 100% completion of all work to takt. DPR counted the number of completed takts in the overall plan over the span of a week and divided it by the number of takts to be completed that week, resulting in a Weekly Takt Percent Completed (Figure 22). They also tracked cumulative values.

WEEK OF	7/16/18	7/23/18	7/30/18	8/6/18	8/13/18	8/20/18	8/27/18	9/3/18	9/10/18
Completed Takts	50.3	50.2	45.8	45.2	47	46	42	47.1	43.8
Weekly Total Takts	54	54	49	47	47	48	44	49	49
Weekly Takt Percent Completed	93.15%	92.96%	93.47%	96.17%	100.00%	95.83%	95.45%	96.12%	89.39%
Cum. Completed	686.6	736.8	782.6	827.8	874.8	920.8	962.8	1009.9	1053.7
Cum. Planned	698	752	801	848	895	943	987	1036	1085
Cumulative Takt Percent Completed	98.37%	97.98%	97.70%	97.62%	97.74%	97.65%	97.55%	97.48%	97.11%
Completed (with make up)	694.30	748.20	797.80	846.20	895.00	941.00	985.00	1034.10	1079.80
Overall percent Complete	43.34%	46.70%	49.80%	52.82%	55.87%	58.74%	61.49%	64.55%	67.40%

Figure 21: Weekly Tracking of Takt Percent Completed
(Weeks of July 16 to September 10, 2018)

WK23	WK24	WK25	WK26	WK27	WK28	WK29	WK30	WK31
7/16	7/23	7/30	8/6	8/13	8/20	8/27	9/3	9/10
1								
1	0.8	0.5	1	1	1	1	0.4	0
1	1	0.5	1	1	1	1	0.4	0.6
1	1	0.5	1	1	1	1	1	1
0.8	1	0.5	0.6	1	1	1	1	1
1	1	0.5	0.6	1	1	1	1	1
94%	89%	73%	92%	100%	100%	100%	82%	86%

Figure 22: Assessment of Takt Percent Completed

Figure 23 charts the number of takts planned- and the number of takts completed each week. The dip in the middle corresponds to the week of July 4th that had been designated as a buffer week. In that week no new work was planned, but Trade Partners could complete go-back work.

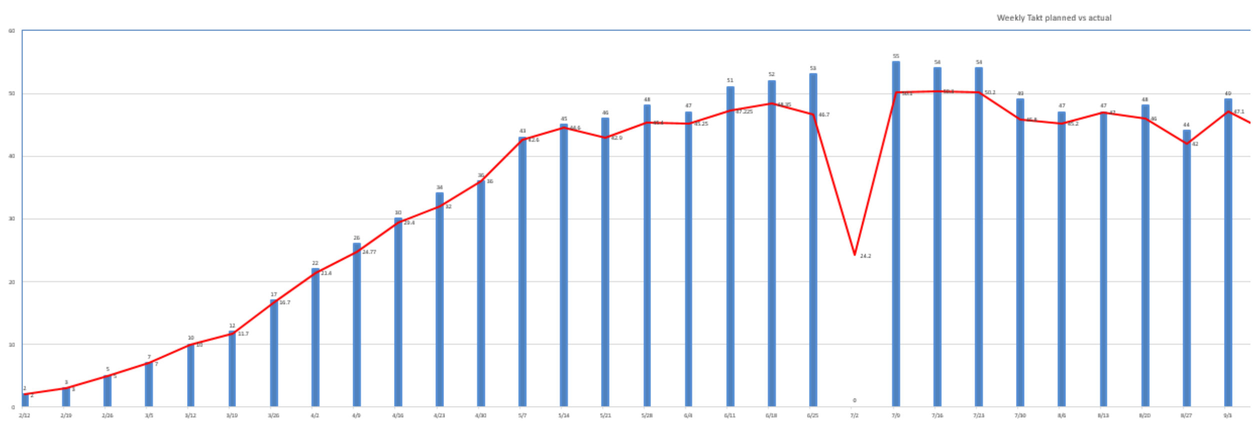

Figure 23: Weekly Tracking of Number of Takts Planned (blue bars) and Number of Takts Completed (red line) (Weeks of February 12 to September 3, 2018)

On this Project, DPR did not "formally" use the Last Planner® System to create reliable workflow. Although the team's Weekly Takt Percent Completed was quite high, on a number of occasions the degree to which takted work had in fact not been completed derailed some follow-on work. DPR might have more thoroughly verified claims of done-ness. Honestly assessing whether or not work is done-done while implementing the Last Planner® System and immediately learning from failures would have enabled DPR to improve its team's performance to takt and the Project's delivery overall.

5. PROJECT DELIVERY CHALLENGES

5.1. Unforeseen Circumstances

Unforeseen circumstances challenged the Project. The San Francisco Bay Area suffered through a drywall tapers strike for one week in June 2018. This delayed the takt impacting the surrounding trades. After the strike ended, DPR's fit-out team considered shifting the takt by a week. However, it was more cost- and time effective to use Saturdays and swing shifts for the impacted go-back work. This allowed for trades to maintain their continuous flow with minimal disruption.

5.2. Decoupling Core-and-Shell from Interior Fit-out Work

Decoupling phases of construction work, thereby allowing those phases to overlap and progress more in parallel with one another (fast-tracking) rather than execute them sequentially, can expedite project delivery. This strategy was effective in the delivery of Merck's VBF facility (see Section 3.5).

The South San Francisco project was broken down in two parts: Alexandria's core-and-shell and Merck's interior fit-out. The two parts had different delivery structures and demand rates yet were to follow each other in close succession. The core-and-shell needed to accelerate their schedule in order to stay ahead of the interior work. Due to structural steel supply issues, the work sequence for steel erection and concrete pours had to change. Structural steel and concrete work fell behind schedule and impeded the succeeding work. The takt plan's visual nature highlighted conflicts throughout the building although the impact was not all negative. For example, a benefit of the delay was that DPR's interior fit-out team was afforded the opportunity to coordinate and place slab embeds before concrete was cast.

5.3. Need for Better Work Structuring

Certain aspects of the Project were not sufficiently called out in the takt plan, e.g., details of finish trades and equipment start-up requirements. For takt planning to be successful, Trade Partners including commissioning agents and start-up team members need to be open with the team and truly express their work preferences, means and methods, trade-specific work flows, and sequencing with other trades, while at the same time being ready to balance them against project realities with the entire team. Such openness demands willingness and ability to realistically forecast and adjust crew sizes. An open discussion with all team members' wants and wishes on the table, will allow the team to develop a zoning and takt plan to decide on a plan for non-takted work, to account for the Trade Partners' preferred work flows while ensuring that the Project's requirements are met.

Hand-off descriptions in the takt plan should specify one-by-one when and which equipment or other one-off work, in which takt or non-takt zone, has to be started up and tested by the commissioning agent.

The team's work structuring efforts should investigate the advantages and production system consequences of takting vs. not takting certain work, and of switching from one zoning-takt scheme to another zoning-takt scheme as work progresses while recognizing, e.g., Trade Partners' preferred work flows. Systems that are constructed piece-meal (e.g., installation of sections of HVAC duct) may lend themselves better to smaller zoning, than systems with continuous runs (e.g., pulling of wire from the electrical room to the end of the distribution).

When teams get good at takt planning, they may find themselves spending proportionally more time on planning the one-off work (Frandson 2019b).

6. CONCLUSIONS

Lessons learned from this Project's takt plan development and implementation include:

1. The decision to takt a project must be made early in design. This is the same as for the decision to use modular construction and to fabricate off-site, which also must be made early in design.
2. Those involved early-on in the project can develop a preliminary takt plan to determine feasibility of a fast project schedule (takt planning as execution strategy), then relay that takt plan to Trade Partners (takt planning as operational strategy) at the time of on-boarding, and further refine it with everyone's input later.
3. Early Trade Partner engagement in design brings construction knowledge to the forefront, which can help to structure supply chains and on-site work for accelerated delivery using takt. This was not accomplished on this Project to the extent it could have been.
4. Trade Partners must be informed prior to contracting that they will engage with the team to takt their work. They must be trained in takt planning prior to and as they on-board with the project.

5. Much of a project's repetitive as well as non-repetitive work can be planned with takt. Generally speaking, more work scheduled with takt is better, because of the benefits achieved with takt planning. On this Project, the takt plan for the Overhead MEP work was structured well. The plans for other work might have been structured better using different takts and zoning.
6. Takt times and corresponding zones will vary with the nature of the work and Trade Partners involved. Expect takt and zones to change from one project phase to the next (e.g., Overhead MEP-, In-wall-, Finishes-, and Commissioning phases).
7. Methods are in place to takt component-based work (e.g., installation of unit materials and assemblies). In contrast, further study is needed on how to structure systems-based work (e.g., commissioning) so that it too can be planned satisfactorily with takt.
8. Don't expect that all work will be part of a takt train. Projects often have one-off work (e.g., Magnetic Resonance Imaging (MRI), Nuclear Magnetic Resonance (NMR), autoclave, rack wash, elevator lobbies, data equipment, specialty rooms, leave out bay, and penthouse) that due to their unique complexity is better scheduled separately and possibly without takt.
9. Takt planning is a work structuring method that goes hand-in-hand with the Last Planner® System. Don't implement one without the other.
10. In accordance with the Last Planner® System, projects should maintain a workable backlog of tasks that can be done in case work in a takt train finishes early or falls through.
11. Areas not on a takt plan must be tightly coordinated (e.g., work in the corridors was coordinated on a daily basis).
12. Separate resources must be dedicated to work that is takted versus non-takted, e.g., for electrical installation work versus equipment start-up.
13. Procurement and long-lead items require their own delivery schedules. Should these not be reflected on a takt plan, they must nevertheless be synchronized with those plans.
14. Once takt trains have been established, adjusting the schedule is straightforward by throttling crew sizes. Takt allows for multiple trains to run in parallel (e.g., staggering of floors as was the case on this Project) or for a train to speed-up or slow-down in order to meet the overall schedule's demand.
15. Time buffers are needed in or between takt trains to articulate the time to perform go-back work, rectify failed inspections, etc. In case of failure, causes must be identified, lessons learned, and process capability enhanced to avoid such rework.
16. Weekends and holidays (and holiday weeks) naturally offer buffering opportunities. While adding buffers means adding time to a schedule, that time allowance helps prevent reverberations through the schedule in case tasks need make-up time.
17. Takt plans offers visual benefits in comparison to traditional Gantt charts (Pearce, Clark, Mirkovich 2018).

Recognizing that takt planning in the construction industry is still relatively new, this documentation of the successful implementation of takt planning on this Project should help inform and educate future takt-planning project teams. It is the fine-tuning and use of all these practices in combination that will allow for ever-faster project execution.

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