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ABOUT TIME-COST TRADE-OFFS IN TAKT PLANNING

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ABSTRACT

Time-cost trade-off problems in construction scheduling are well known and described in the literature, but time-cost trade-off problems pertaining specifically to takt planning have received little attention to date. Previous papers have introduced concepts and applications of takt planning (aka. takt production) in construction. They addressed production systems design questions and presented various takt planning methods. Quite a few of those papers also mentioned how takt planning helps cope with variability that is known at the time of planning and with the manifestation of variability when it is encountered during plan execution. Coping methods include the use of capacity- (people and their means of production), materials- (inventory), space-, and time buffers. These buffers—and of course money too (financial buffers or contingencies)—come at a cost. This paper explores various costs to be considered in the takt planning process and it presents trade-offs that can be made to meet selected objectives. The goal is to initiate discussion on this topic and help spur further quantification of the advantages of using takt when designing project production systems.

KEYWORDS

Takt planning, buffers, slack, direct cost, indirect cost, fixed cost, variable cost, cost management, buffer management.

INTRODUCTION

While time-cost trade-off problems in construction scheduling have been studied extensively for many decades, time-cost trade-off problems pertaining specifically to takt planning have received little attention to date. To investigate the latter, this paper revisits the assumptions that underlie basic time-cost trade-off formulations and then scrutinizes those assumptions in light of the application of the lean concept “takt” used in the development and control of construction schedules. Note that the terms planning and scheduling are used interchangeably in this paper.

This conference paper is not a formal literature-review or research-based paper but rather a white paper reflecting the author’s thoughts on time-cost trade-offs in takt planning. Essential parts of a formal study (e.g., an in-depth literature review) are therefore not included here but deferred until a later time. A white paper is meant to be thought provoking.

This paper is structured as follows. First, the literature section describes the basic formulation of the time-cost trade-off problem in construction scheduling. It then describes key concepts pertaining to takt planning in construction. The body of the paper elaborates on tangible and intangible time-cost benefits of takt planning. This is followed by a discussion on time-cost trade-off considerations, and conclusions with recommendations for further research.

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LITERATURE

TIME-COST TRADE-OFFS IN CONSTRUCTION SCHEDULING

The time-cost trade-off problem in construction scheduling has been studied since the early days of the critical path method (CPM) (e.g., Kelley 1961) and has become a fundamental topic in project management textbooks (e.g., Ch. 10 in Harris 1978, Ch. 11.4 in Hendrickson et al., 2024). Numerous variations of this problem have since been formulated, based on different assumptions with resource- and other constraints added, and using various mathematical programming- or heuristic optimization methods.

The problem is formulated by means of activities networked using precedence relationships (e.g., finish-to-start links) to make up a construction schedule (essentially a directed graph). Each activity is given a duration (e.g., modelled using a deterministic value). Each activity comes at a cost (e.g., also a deterministic value) in function of what it takes to perform the associated work using a certain resource allocation (workers with tools, equipment, materials, etc.) so that the activity can be completed within the specified duration with reasonable certainty. By definition, direct costs of an activity are costs that would not be incurred if the activity were removed from the schedule. A (piecewise) linear relationship is assumed between the so-called normal duration at the normal cost of an activity and its crashed duration (shorter than the normal) at the crashed cost (higher than the normal).

Given the network's precedence relationships and activity data, the project's direct cost and duration defined by the so-called critical path(s) can then be computed. An activity is said to be on the critical path—it is a so-called critical activity—when, if delayed in finish time, the entire project would be delayed. A critical activity has no float.

Starting from the normal duration and normal cost for each activity, the project duration can be shortened while its direct cost will increase. A heuristic method for doing so is to stepwise shorten the duration of the critical activity (or several critical activities in parallel) that is the least costly to shorten. For example, the order in which to crash activities shown in Table 1 is F, C, C, B and C, A, and finally B and C.

Table 1: Example activity network with time- and cost data (Tommelein 2023)

Activity	Finish-to-Start Predecessor	Normal Duration [days]	Normal Cost [$]	Additional Cost/Day Shortened [$/day]	Minimum Duration [days]
A	-	3 days	$1,800	$800/day	2 days
B	A	4 days	$2,000	$200/day	2 days
C	A	5 days	$1,000	$150/day	1 day
D	C	1 day	$400	--	1 day
E	A	3 days	$1,500	$500/day	1 day
F	B, D, E	2 days	$700	$100/day	1 day

In addition to direct costs, projects also incur indirect costs. Sometimes called general conditions costs, these are not straightforward to attribute to only one or a few activities, but instead are more related to the project as a whole (e.g., the costs of project supervision, gate access and fencing around the site, provision of temporary utilities). They tend to accrue in direct relation to the duration of the project and are typically modelled as a linear function of time, expressed as cost per time unit (e.g., $300/day). Accordingly, they decrease (or increase) with the decrease (or increase) of the project duration. A project's total cost is the sum of its direct- and indirect costs.

Figure 1 depicts the direct- and indirect costs for different durations of the project. It shows that the plot of the project's total cost vs. time—called the time-cost trade-off curve—may exhibit a minimum rather than steadily increase or decrease. That minimum total cost point is the optimum duration for the project (indicated on Figure 1 at 8 days and $10,200) in the sense that the project will cost more when scheduled to be of any other duration, longer or shorter.

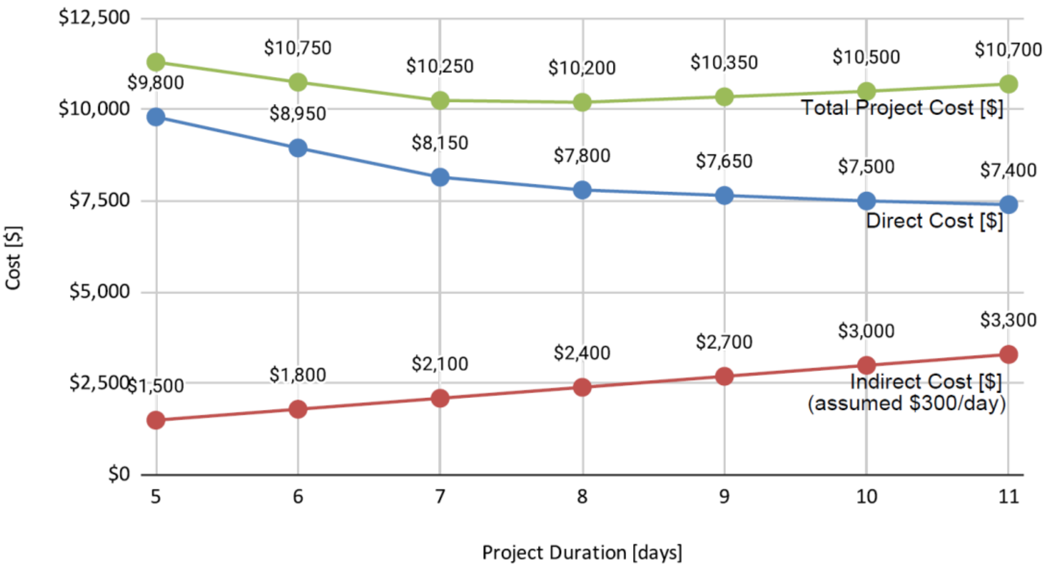

Figure 1: Time-cost trade-off in CPM scheduling (Tommelein 2023)

Note that the classification of a cost as direct or indirect depends on one's point of view and choices informed by the commercial terms of a project, including the cost accounting system in use. Figure 2 illustrates contributors to a company's and its projects' direct- and indirect costs. General and administrative (G&A) expenses are direct costs for the company, i.e., if the company did not exist, these costs would not be incurred. As they must be paid for in some way, they may be treated as indirect costs by accounting for them as an overhead charge on each project the company performs (e.g., as a percentage of a project's direct- plus indirect costs).

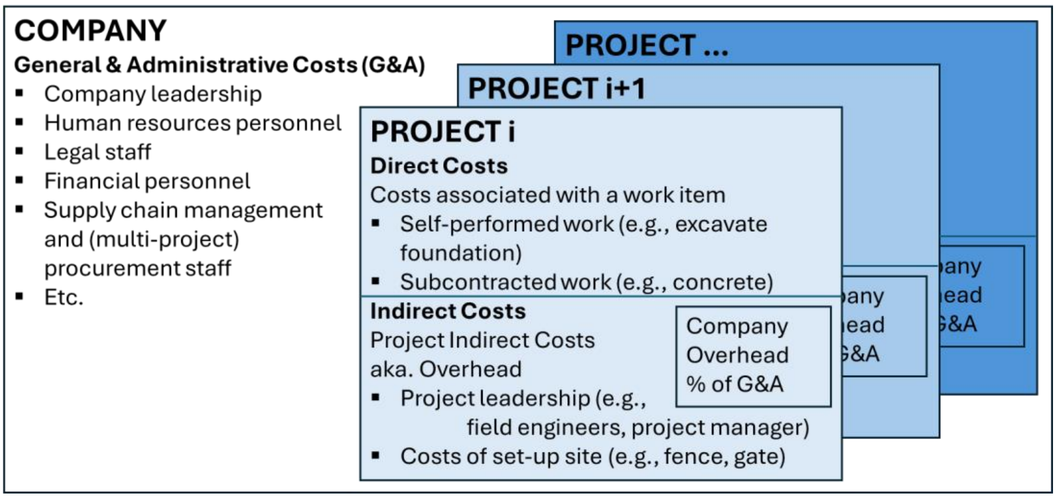

Figure 2: Contributors to direct- and indirect costs for companies and their projects (Tommelein 2023)

With this basic description of the time-cost trade-off problem and cost-related definitions pertaining to construction schedules in general, we next focus on takt planning, before we get into time-cost trade-offs related to takt plans (aka. takt schedules), a specific type of construction schedules.

TAKT PLANNING (AKA. TAKT PRODUCTION)

Practitioners and scholars alike have taken interest in defining a takt when planning construction processes (e.g., Frandson et al., 2013; Linnik et al., 2013; Heinonen & Seppänen 2016; Dlouhy et al., 2016, 2018; Binninger et al., 2017; and Lehtovaara et al., 2019). Despite this interest and the occasional mention of cost in takt-related papers (e.g., Vatne & Drevland, 2016), time-cost trade-offs problems pertaining specifically to takt planning have received little attention to date. In fact, a search for "time-cost" in papers posted on IGLC.net identified only a single one (O'Brien et al., 1997). It pointed out that the basic time-cost trade-off problem formulation ignores capacity constraints (e.g., resource availability, resource utilization, and site conditions) encountered when a schedule gets accelerated or delayed. We were unable to locate any prior studies on the specific topic of time-cost as it relates to takt planning.

In takt planning, the work to complete an entire construction project or a phase thereof is broken down into processes, with each process comprising steps arranged finish-to-start in linear order. The scope and sequence of these steps is decided while considering where work is to be done and avoiding trade stacking. Then the work space is divided into zones so that each step can be completed in each zone within the same, fixed amount of time, defined based on the duration needed to meet customer demand (T), aka. the "customer takt". The work is structured so that only a single trade is working in any one zone at any given time while aiming to achieve continuous flow (e.g., Formoso et al., 2022).

Flow (i.e., a smooth progression of something, said to be "continuous" when there are no interruptions) manifests itself in multiple ways (Tommelein et al., 2022) which can be measured (e.g., Singh et al., 2020; Singh and Tommelein, 2023a, 2023b), e.g., (1) When a step is completed in one zone, the succeeding step of the same process can start there, and (2) At the same time, the trade that completed their work moves to start work in the next zone, etc. Thus, trades flow from one location to the next (Tommelein et al., 2022 called this "trade location flow") and work in each zone gets done in the process order of successive steps ("process location flow").

By creating concurrency of steps, the project can be completed faster than it would be otherwise (Figure 3). The cost for shortening the schedule duration will be a function of the trade location flow, process location flow, and many other metrics, and their costs. Using these, takt planners can then make trade-offs as needed to balance the degree to which they can meet their objectives.

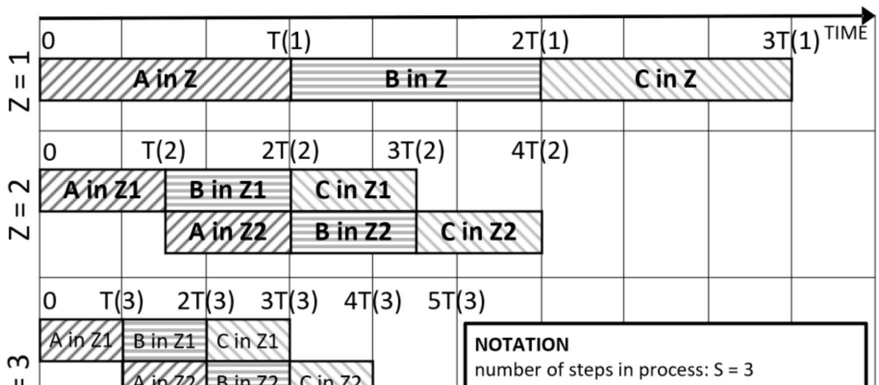

Figure 3: Duration of 3-step process (steps A, B, and C) when the work area

is divided into respectively 1, 2, and 3 zones Z (after Figure 1 in Jabbari et al., 2020)

Because workloads will exhibit some variability, any individual workload (i.e., the actual time needed by a trade to complete a certain scope of their work in a given zone) should be less than the time T allotted. How much less is a function of a workload's variability: trades must reasonably ensure that each step-worth of work will be completed by time T. This ensurance is obtained by underloading resources and thereby creating a capacity buffer, i.e., by scheduling resources to work below 100% utilization. The use of right-sized capacity buffers makes it possible to achieve plan reliability (Frandson et al., 2015).

In any case, at least one trade will have a workload greater than everyone else's and that is called the workload peak, aka. the "operational takt." The workload peak must be smaller than or at most equal to the time T allotted or the customer demand will not be met. As this workload peak is a function of the way zones are defined, it is labelled T(Z), with Z referring to a specific zoning of the space where work is to take place. Thus, the zoning and takt plan must be structured so that $T(Z) \leq T$.

Once the workload peak (possibly with an allowance to account for variability) of a process is known for a certain zoning of the work space, the shortest duration D of that takted process can be computed mathematically:

$$D = (S + Z - 1) \times T(Z) \quad \text{(Equation 1)}$$

where S is the number of process steps, Z the number of zones, and T(Z) the workload peak. An increase in the number of zones Z typically results in a decrease in the duration D, as zones get smaller in area and T(Z) tends to go down (up to a point, as noted in Jabbari et al., 2020).

Several methods exist to zone a work space. For example, as a tool to support the use of the Work Density Method (Tommelein 2017, 2022), Jabbari et al. (2020) described a mathematical algorithm, the Workload Leveling and Zoning algorithm aka. WoLZo. WoLZo uses a given distribution of workloads for each trade in the work space and the number of zones dividing the work space, to calculate the optimal boundaries for zones (constrained to be either rectangular or L-shaped), i.e., the zoning that results in the minimum operational takt T(Z).

Given this brief review of the literature on the time-cost trade-off problem and on takt planning, the following section opens the discussion about time-cost trade-offs in takt planning.

TIME-COST TRADE-OFF CONSIDERATIONS IN TAKT PLANNING

Float in a Takt Plan?

Now return to the basic description of the time-cost trade-off problem with solution methods that stepwise reduce the duration of one or several critical activities. Note that all steps in a takted process follow each other sequentially as in a Parade of Trades and they all are given an equal duration (Tommelein et al. 1999; Tommelein, 2020). Unless an explicit time buffer is incorporated in the process (e.g., a 1-takt delay, perhaps to allow for make-up work), there is no float from start-to-end of a process: all steps are critical. Time-cost optimization methods must therefore be rethought.

Indirect Cost when Shortening the Duration of a Process or Project

The argument may still hold, given the previously stated assumptions about overhead rates, that shortening the duration of a project will result in less indirect cost. Whether shortening the duration of a process (presumably one of several processes in a project) will also shorten the duration of the project depends on how that process fits into the project network.

We can extend the notion of criticality of an activity and identify critical processes in a project. However, it is common practice in takt planning to strategically include time buffers not only within- but also between processes to prevent any delays from reverberating through the schedule (Binninger et al., 2017). Teams pursuing takt planning must proactively manage their work to prevent a Parade of Delays (Dahlberg and Drevland, 2021) and should be cognizant of slack in their production system available to help them cope with unforeseen circumstances (Formoso et al., 2021). The practice of adding time buffers to a takt plan is similar in spirit to adding feeding- or project buffers to a schedule when using the Theory of Constraints (TOC) (Goldratt, 1990), or to adding a schedule contingency before the project completion date. When time buffers are added, then all processes have float.

Revisiting the assumption about the overhead rate, note that shortening a project or process by creating more concurrency in the schedule increases the schedule density (schedule density is a term used in construction claims; see for example Finke, 2000 or Ottesen and Hoshino, 2014). Otteson’s (2019) thesis is that an increase in schedule density is a predictor for productivity loss. More activities underway in multiple locations at the same time and greater interdependence between them may result in greater complexity that in turn may require more managerial attention. Consequently, an increase in the need for managers could warrant an increase in the overhead rate.

However, the structure of the schedule, in and of its own, captures only a small part of the reality of a project. Team engagement and managerial practices play a role in project delivery! On takted projects, the shared understanding developed among trades during the takt planning process, and the visual- and structural clarity of the takted schedule (e.g., Figure 3) could be such that no additional managerial attention will be required when the schedule density increases. We speculate that research might even indicate that successful execution of a takt plan demands less managerial attention.

Cost of Shortening the Duration of a Process

The duration D of a process can be shortened in several ways, as indicated by the terms in Equation 1, namely by:

- Reducing the number of steps S in the process. This may be possible by moving work from one step to other steps (or combining steps) in the same process, by moving work to another activity or process step elsewhere in the project schedule, or by taking scope out from the on-site work and moving it off-site. A reduction of D in this way can either increase or decrease the project cost depending on capacity constraints (e.g., O’Brien et al., 1997), network characteristics, and the related economics.
- Increasing the number of zones Z to allow for more concurrency, if doing so indeed reduces T(Z) and has the effect of lowering D. The indirect cost implications in this case already were discussed in the previous subsection. As for the direct cost implications, in a first-order approximation, shortening the duration may be cost neutral as each trade’s total amount of work and resources stay the same. In a second-order approximation, however, consideration must be given to costs stemming from work interruption or remobilization penalties. These are discussed later, in the subsection Cost of Logistics.
- Reducing work densities (e.g., by adding more resources) to lower the workload peak in a process, so that T(Z) can be lowered either in and of its own or by rezoning. Adding resources clearly comes at a cost. However, knowing which process step(s) essentially determine the workload peak also reveals which trade(s) in which zone(s) have a much smaller workload than others. These trades can use the process workload data to identify when and where they can slow down without jeopardizing the duration of the process. By assigning fewer resources, they can lower their cost while increasing their work density (not to exceed the workload peak) in certain or all zones. In combination, such cost changes due to increases and decreases in resources can have a positive or negative impact on the cost of the process.

When the workloads of all steps in a process are more-or-less balanced across trades and zones, resources presumably are used efficiently, and a near-continuous trade location flow and process location flow will be achieved.

Cost of Capacity Buffers (Underloading)

Whereas all steps in a takted process are critical, looking closer at the workload for each step in each zone it is noted that resources are underloaded. This is so by construction. Indeed, the intentional use of capacity buffers is what sets takt planning apart from other planning methods such as the Location Based Management System (Frandson et al., 2015). Underloading means that resources have a modest amount of extra capacity to do more work if needed, e.g., due to the manifestation of variability, and still finish each step on time. The whole point of takting a process (underloading resources at each step) is to allow handoffs to occur like clockwork, so as to prevent delays from occurring and impacting follow-on work.

Underloading comes at an increase in cost directly tied to a process step. Arguably, paying for intentional underloading is the greatest challenge to overcome when introducing takt planning to a team that is narrowly focused on productivity. Underloading brings benefits to the schedule, such as robustness, by creating slack time for trades to respond to disturbances encountered during plan execution.

Cost of Time Buffers within and between Processes

As was mentioned in the section on shortening the duration of a process or project, time buffers can be added anywhere in a takt plan, e.g., in or towards the end of a process, or in-between processes. Whereas all steps in a process are critical (they must be done within the takt), the process itself can be decoupled from preceding or subsequent processes by means of a buffer, and thus at that level have float.

While the use of a time buffer itself may appear to be free (a no-cost option), the buffer may extend the project duration and therefore result in an increase in indirect costs. Time buffers can also cause resources to be idle, having to wait for work, resulting in increased direct- or indirect costs depending on how the accounting is done. Trades involved in takt planning must duly consider how to use their time on site waiting until the next zone becomes available, e.g., by judiciously creating learning opportunities or workable backlog, in order to avoid otherwise unproductive wait times.

Cost of Space Buffers

Like time buffers, space buffers may appear to be free (a no-cost option), but that is not the case. They indicate a wasted opportunity to complete a process faster as work is waiting on workers. The availability of open spaces may tempt people to use them and as a result, materials handling and work practices may not be as well thought-out as they could be. Moreover, space buffers may not be free even when left open, e.g., when completed work requires protection or conditioning.

Cost of Logistics

Concern about the cost of logistics is often expressed when people hear about just-in-time production with its frequent deliveries of small batches of products—highly relevant to takt planning, especially when a work space is divided into many zones—because their minds are set on efficiencies of scale when producing and transporting large batches of products. It is also brought up in the context of kitting—likewise highly relevant to takt planning (e.g., Tetik et al., 2019, 2021; Gschwendtner et al., 2021). The concerns are valid when new practices are being contemplated. Lean practices such as those mentioned require engagement early on in a project and an up-front financial investment for their implementation. Cost accounting for logistics is complicated, and even more so when logistics is interpreted broadly (e.g., Mossman, 2007, Seppänen & Peltokorpi, 2016).

To illustrate, Figure 4 offers an example of a lean logistics cart used by a mechanical and plumbing contractor. This contractor invested in the development of this mobile, adjustable rack, that will serve not only the current project it is used on, but also future projects. The cost of this rack may be charged to the project for example on a per-use basis. Gschwendtner et al. (2021) accounted for such costs in their study of supply- and reverse logistics to support a takt plan, however they failed to obtain data describing the efficiencies gained by the installation crews that were supplied with kitted materials. Logistics costs are incurred by one group of people and the benefits reaped by others; when too narrowly accounted for, they will not pen out. This is where accounting (e.g., Horngren et al., 2012) and lean accounting systems have a role to play (e.g., Cunningham et al., 2003; Maskell & Baggaley, 2006; Maskell & Kennedy, 2007; and Maskell et al., 2011), to take a broad view on the production system and attribute costs appropriately, as needed here in the context of takt planning.

Figure 4: Example of lean logistics - cart with pre-assembled fixtures
(Source: I. D. Tommelein, 20 April 2016)

DISCUSSION

Taking a step back from these time-cost considerations, it will be clear to the reader that the intuition they may have developed about basic time-cost trade-offs in CPM-type scheduling does not exactly hold for takt planning.

The time-cost trade-off problem was originally formulated in the context of CPM, which is used at the master level of scheduling (using the terminology of the Last Planner® System (Ballard & Tommelein, 2021)). The time-cost trade-off problem as discussed in this paper, however, pertains to takt planning, which affects planning at multiple levels in the Last Planner® System, from master level scheduling all the way down to execution and control. Takt planning is production focused and therefore demands consideration of various kinds of variability in the system given its context, dedicated and shared resources, capacity utilization and allocation, production throttles that can be adjusted in the planning process, etc. All of these affect the cost of the takt plan and may thus be relevant to time-cost trade-offs.

In an effort to instil regularity in a takt plan (e.g., by means of defining process steps and balancing workloads) and aiming to achieve reliability in the execution of each and every step, some costs will have to be incurred (e.g., underloading of resources). This notwithstanding, such investments are expected to pay off and, if not immediately, then certainly in the long term reduce cost. Reliability and visual clarity in the takt plan create the possibility for project participants to tune their resource allocation to systemic needs, rather than exclusively to their own resource availability and company optimization strategy. Furthermore, the clarity in a takt plan's definition creates the stability that makes it possible for team participants to learn and improve their work over time in the course of a single project (e.g., Vatne and Drevland (2016) mentioned that crews were able to reduce their crew size as they speeded up), but also going from one project to the next one (e.g., increase their process capability) (e.g., Tommelein, 2020).

Further study is in order of existing algorithms for time-cost trade-offs—there are so many! It may be possible to use some parts of existing problem formulations (e.g., Feng et al., 2000, Al Haj & El-Sayegh, 2015) to study time-cost trade-offs in takt planning, and it certainly is possible to develop fit-for-purpose computer-based simulation models to allow for experimentation with alternative plans (e.g., Tommelein, 2020; Gschwendtner et al., 2021). Whatever problem formulations and algorithms exist, they will require extensions, e.g., to model various resource types, variability, work density, and other concepts specific to takt planning.

Besides the need to develop new algorithms and computer-based support tools to help takt planners make time-cost trade-offs, more fundamental is the development of lean construction cost accounting systems. This topic is worthy of greater study in our IGLC community, informed by publications on lean cost accounting as it is used in manufacturing and elsewhere.

CONCLUSIONS

Starting from the recognition that problems pertaining to time-cost trade-offs specifically in takt planning have received little attention in the scholarly literature to date, this paper explored various costs that are to be considered in the takt planning process. It raised a number of concerns and recognized a lack of knowledge; knowledge that will be needed to make informed time-cost trade-offs to meet selected objectives.

Only a few of the specifics related to time-cost trade-offs were presented in this paper. An in-depth study of the literature is needed, and formal cost models should be developed to support takt planners, e.g., using lean accounting methods. Our hope is that this paper's exposition of theoretical concepts related to the time-cost trade-off problem in takt planning will initiate discussion on this topic and help spur further quantification of the advantages of using takt in project production systems.

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