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WORK DENSITY METHOD FOR TAKT PLANNING OF CONSTRUCTION PROCESSES WITH NON-REPETITIVE WORK

Iris D. Tommelein[1], M ASCE

ABSTRACT

A new method is presented for construction process planning. It is based on the concept "work density" and called the Work Density Method (WDM), two terms coined for use in this context. Using the WDM, planners create one-piece workflow by dividing work space into zones while assigning each zone exclusively for each trade to complete their work, with trades working in consecutive process steps, each one taking up to the same, fixed amount of time. The method supports development of a plan (using takt or not) for repetitive as well as non-repetitive work thanks to work density serving as the common unit to describe workload. The WDM is an iterative method using work structuring to decide a sequence of process steps, zone the work space while lowering the peak of the cumulative work density (aka. workload peak), determine a lower bound on the takt that can be met, and verify this meets customer requirements. The method was developed experimentally on a live project. This paper rationalizes the use of work density in planning, illustrates the WDM using examples, presents a paradox, and suggests method enhancements. The contribution to knowledge is the formulation of a new planning method that augments existing planning methods.

PRACTICAL APPLICATIONS

On construction projects where speed is of the essence activities must get scheduled in parallel and take place in multiple locations simultaneously. Those locations must be clearly demarcated in order to avoid the detrimental impact of trade stacking, and activity completion times must be strictly adhered to in order to avoid cascading delays. The Work Density Method (WDM) presented in this paper offers a systematic approach to determine such locations and to set a time limit within which activities must be completed. This new method is intended for use by superintendents together with their trade partners to develop an execution strategy so that they will be able to reliably hit milestones shown on their project master schedule. Some planners may already be familiar with the notion of work density and be using it intuitively when considering options to shorten a project's duration. In this paper, a new, formal method is presented. It is illustrated by various examples. The use of computational support tools is suggested for practical implementation.

KEYWORDS

Work Density Method (WDM), Lean Construction, process planning, takt planning, space scheduling, location-based scheduling.

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INTRODUCTION

Since Kelley and Walker (1959) and Kelley (1961) specified the Critical Path Method (CPM), CPM has become entrenched in the construction industry. Numerous variants of CPM have been developed since (e.g., Birrell 1980, Russell and Wong 1993). Even with its specifics, the term has become rather generic in use. "CPM scheduling remains a craft skill with wide variances in methodology and utilization across industries and even within companies based on the past experience of individual schedule practitioners" (Huber and Reiser 2003). In addition to CPM variants, new methods have been and continue to be developed.

The term takt planning, referring to a set of such new methods, is seeing increased use in construction projects around the world and in the scholarly literature, a selection of which includes, e.g., Court 2009, Frandson et al. 2013, Linnik et al. 2013, Haghsheno et al. 2016, Binninger et al. 2017, Tommelein 2017, 2020, Gadbois et al. 2018, Tommelein and Pak 2019, Lehtovaara et al. 2020, Jabbari et al. 2020. Despite an uptake in use, procedural method specifications are lacking. This lack impedes understanding how takt planning can be used and automated to increase performance in the construction industry.

With this in mind, the aim of this paper is to specify a new planning method. This new method is based on the concept "work density" and is called the Work Density Method (WDM). The WDM supports spatiotemporal planning at the process level. Although the WDM can be used to develop a takt plan, it has broader applicability. The paper therefore does not delve deep into takt planning per se (see the provided references on takt planning for that).

In the next section of this paper, an overview of planning and scheduling methods as described in the literature helps to position the WDM in this context and clarifies the WDM's novelty. The section thereafter presents the theoretical underpinnings of the method based on the notion of process flow. The "Work Density Method" section introduces work density as a means for instilling process regularity in work that otherwise may be deemed non-repetitive. Based on this concept, it then describes the WDM that includes lowering work density peaks to an acceptable level by (re)zoning the work space (e.g., as needed to inform the selection of a takt). The three sections thereafter illustrate the application of the method and point out counterintuitive, somewhat paradoxical findings. The "Discussion" section stresses the novelty of the term work density as used in this paper, compares the WDM with other planning methods, and expands on several of the modeling assumptions made. It also suggests the use of computational support tools for practical implementation of the method. The final section of this paper concludes with recommendations for further theoretical research and practical application to enhance the WDM.

RELATED LITERATURE ON PLANNING METHODS

Methods Matter

Given the variety and number of resources that may be considered in planning, the intricacies of how work can be done, possible interdependencies between activities, numerous objectives one can set out to meet, etc., no single planning method—even when provided with all requisite inputs—can reach an optimal solution in all regards. Planning methods tend to be path dependent. This means that the plan solution obtained is a function of the assumptions made, chosen inputs, starting point, and steps taken to reach the solution. Moreover, planning is a balancing act: it typically requires multi-objective optimization with objectives at odds with one another. In turn, how a method gets formulated determines the computational requirements to obtain satisfactory- or optimal solutions. For these reasons, planners must understand the differences between methods so that they can choose the best one for the problem at hand: method selection matters (also see Kenley and Seppänen 2009b).

Spatiotemporal Planning Methods

The literature describes different construction planning methods. Some methods model space explicitly and are therefore called spatiotemporal planning methods. The need to account for space is acknowledged in other planning methods as well, albeit more implicitly. Indeed, space was a concern expressed even in the early days of CPM. Kelley and Walker (1959 p. 162) recognized: "[I]n order to prepare for the scheduling aspects of project work, it is necessary to consider the environment of each job. For example, on the surface it may be entirely feasible to put 10 men on a certain job. However, there may only be enough working space for five men at a time. This condition must be included in the job's definition. Again, it may technically be possible to perform two jobs concurrently. However, one job may place a safety hazard on the other. In consequence, the first job must be forced to follow the second." Notwithstanding the omnipresence of space, planners may overlook the need to address its availability and allocation.

Several comprehensive review papers on spatiotemporal planning have appeared in recent years including those by Andayesh and Sadeghpour (2014), Sadeghpour and Andayesh (2015), Ardila and Francis (2020), Igwe et al. (2020), Xu et al. (2020), and Al Hawarneh et al. (2021). That being the case, this paper does not offer another comprehensive review on this topic but instead highlights key differences. In a nutshell, space has been represented in plans as non-dimensional (e.g., the name of an activity in a Gantt chart may refer to a location such as "Place concrete on level 5."), one-dimensional (e.g., space is indicated on the horizontal axis of a diagram marking for example stations along a road, with time on the vertical axis, or vice versa), two-dimensional (e.g., time-dependent layout diagrams), or three-dimensional (e.g., a Building Information Model (BIM) model tied to a schedule). The spatiotemporal model described in this paper represents space in two dimensions. In contrast to approaches that model space either at the workface (e.g., Akinci et al. 2002) or in other locations where a trade needs it for some amount of time such as for layout or assembly (e.g., Sadeghpour and Andayesh 2015), it handles both.

Repetitive Scheduling Methods

Repetitive scheduling methods (Harris and Ioannou 1998) and location-based methods (e.g., Kenley and Seppänen 2009a) rely on identifying units of work (which may be units of space) that are built repeatedly in order to create regularity in the schedule. This is done by dividing the work according to a Location Breakdown Structure (LBS) (or other repetitive unit of work) and then scheduling it while aiming to achieve resource continuity (flowing resources through different locations as is done, e.g., in the line-of-balance method). Alternatively, it is done by dividing the work according to Standard Space Units (SSUs) and then leveling the trades' work by SSU while takting the process, aiming to achieve a more even process flow (e.g., Binninger et al. 2017a). In contrast to these two approaches, the model described in this paper does not start, a priori, with a LBS or SSUs, but instead it adjusts the boundaries of the locations where work is done (called zones) as a means to help lower the workloads. In turn, lower workloads make it possible for the trades to succeed each other faster, and to lower the takt in case takt planning is used.

In summary, the novelty of the WDM relative to existing models lies in the combination of what types of spaces are modeled and when those spaces are defined in the planning process.

THEORETICAL AND PRACTICAL UNDERPINNINGS OF THE WORK DENSITY METHOD

Certain concepts and vocabulary are introduced next to situate the WDM in the context of lean thinking in construction including takt planning and planning in general.

Conceptual Foundation of Takt Planning

The term takt planning refers to a set of planning methods where activity durations are constrained in time by a takt. Takt is the German word for beat, namely the maximum unit of time within which a product must be produced (supply rate) to match the rate at which that product is needed (demand rate) (Hopp and Spearman 2011). At the operational level, takt planning methods aim to pace work to a regular beat with evenness in workflow and avoiding trade stacking. They shape the work in a line flow system. At the strategic level, the takt reflects the external requirements imposed by the cash customer (the entity that pays for the project) and others in terms of time granted to complete a process, phase, or project.

Complementing the concept of takt that captures external demand and informs how fast the system should produce (e.g., activity completions, handoffs), is the concept of cycle time that captures the system's internal ability and describes how fast the system can produce. Cycle time is the time needed to make a product for a customer. It can be the total duration of the value stream, which comprises "All of the actions, both value-creating and nonvalue-creating, required to bring a product from concept to launch (also known as the development value stream) and from order to delivery (also known as the operational value stream)" (Marchwinski 2014 p. 116). At the highest level of planning, cycle time is the time needed to deliver a project (the schedule's duration). At more detailed levels of planning, cycle time respectively refers to the time needed to complete a phase of work, to complete a process, or to perform a step in a process or operation.

Interest in takt planning is rooted in concern that the drive to increasingly compress construction schedules (i.e., reduce cycle time) has hampered project delivery performance. Indeed, schedule compression achieved by driving out float tends to cause more activities to overlap in time and space, and consequently increase the number of critical paths in the schedule and potential spatial clashes. This creates challenges because variability will manifest itself in project execution. Such challenges include the need to address merge bias (which describes that any one of several merging paths that get delayed can affect the start of a successor activity) and delay of any critical activity that can reverberate through the remainder of the schedule, ultimately pushing out the project end date.

The construction industry—ever-so focused on productivity—has an opportunity to improve project performance by considering productivity simultaneously with cycle time while recognizing that performance trade-offs must be made according to these and other metrics (Shingo 1986 p. 15). The notion that improving productivity alone may not have an impact on the cycle time is known as the productivity paradox (e.g., National Research Council 1994). As for the productivity vs. cycle time trade-off, Rother and Shook (1998), Modig and Åhlström (2015), and others (in construction, e.g., Binninger et al. 2019) have argued that reducing the cycle time of a value stream must come before focusing on productivity. This makes sense because cycle time is a system characteristic. Improvements so identified can then inform investment in productivity improvement. In contrast, productivity of a resource describes point speed. Improvement of point speed does not necessarily benefit the system at large.

Aiming to deliver a project that meets stakeholders' demands (e.g., project milestones), takt planning methods adjust cycle times so that it will be possible to reliably hit target dates. By stabilizing the system based on takt and avoiding trade stacking, they create "ideal" work conditions where productivity improvements can be identified and implemented. Takt planning methods set a beat to instill steadiness in performance of the work and define clear handoffs between trades to facilitate coordination and control. They first reduce variability to ascertain process capability and then insert capacity- and other buffers to absorb potential impact of the manifestation of any variability that remains (Horman 2001, Frandson et al. 2015, Dlouhy et al. 2019, Tommelein 2020). Finally, they rely on the use of rapid feedback, at least every takt, to ensure plan reliability. These theoretical underpinnings drove the development of the WDM.

Calculation of Process Duration Based on Takt

Consider the following rationale for planning. If work is to be done by multiple trades involved in a process in a certain work space and only one trade at a time can work in that space (never stacking trades), then the duration needed to complete that work with trades working sequentially is the sum of the durations each trade needs to complete their own work. To shorten this duration, a planner may divide the work space into zones (with zones being mutually exclusive and collectively exhaustive) then assign each trade to work exclusively in a zone and to work successively in different zones. In general—although not always—when the number of zones increases, zones will get smaller and have less scope for each trade to complete. Thus, trades will need less time to complete their scope prior to moving to the next zone. The time each trade needs will vary based on how zones are defined. The time needed for all trades to complete their work is the process duration and it can be computed as is explained next.

Using the nomenclature from Jabbari et al. (2020), let S be the sequence of steps in the process for completing a certain scope of work, where each step is performed by a certain trade. A trade may perform multiple steps. Let Z refer to the number of zones in which a work space gets divided, with zones differing possibly in size and shape from one another. Since the time a trade needs to complete a step—here called their workload—will vary by scope, means-and-methods selected, crew sizing, etc. as well as how zones are defined, let T(Z) refer to the maximum of those workloads considering all steps and all zones—this maximum is called the workload peak. To illustrate, Figure 1 presents schedules of a takted process with 3 steps where the work space is divided respectively in 1, 2, or 3 zones.

For simplicity, this workload peak is here referred to as the takt but to be correct the takt should be determined by adding extra time (i.e., a capacity buffer) to T(Z) as a means to acknowledge variability in step completion times. Based on the desired process performance level, this buffer must be sized as needed to have the desired confidence in the likelihood that each step will indeed be completed within the takt. Trades must guarantee the capacity to meet the takt in order to avoid

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that any delay would reverberate through the plan. While the elimination of such process time variability and subsequent buffering for any that remains are of utmost importance to the potential success of a takt plan's implementation, the specifics on managing this variability are beyond the scope of this paper.

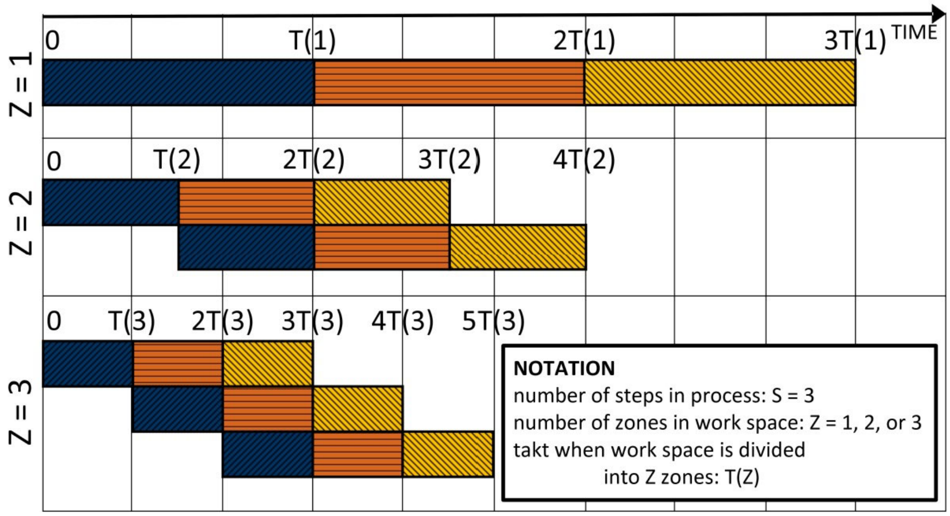

Figure 1: Three alternative takt plans of a 3-step process with work space divided respectively in 1, 2, or 3 zones

Let D refer to the duration of the process. D is calculated as the sum of (1) the number of steps S in the process and (2) the number of zones Z minus 1, multiplied by the workload peak T(Z) (Equation 1).

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

Figure 1 suggests that an increase in the number of zones allows for greater concurrency of process steps. This is generally true but there is a caveat (more on this later in the paper): as Z increases, one might expect zones to become smaller and T(Z) as well as D to decrease. To the extent that this indeed the case, Equation 1 shows that by dividing the work space and accordingly recalculating T(Z) the duration can be shortened as needed to match the requirements imposed on the schedule (project milestones). An implied assumption is that resources will be at the ready to complete each step.

LEVELS OF PLANNING

The terms defined next will make it possible to specify the WDM and situate it relative to other planning methods. Kelley and Walker (1959 p. 161) "defined planning as the act of stating what activities must occur in a project and in what order these activities must take place. Only technology and sequence were considered. Scheduling followed planning and is defined as the act of producing project timetables in consideration of the plan and costs." In everyday language, planning and scheduling are often used interchangeably, and this is the case here too.

The following description relies on terms from the Last Planner® System (Ballard and Tommelein 2021). The **master schedule** of a project may comprise one or multiple phases. A **phase** is the hinge point between project planning and production planning. It is defined by a certain scope of work done by trade specialists (subcontractors) who will work more-or-less concurrently in a certain **work space**. Each phase has a start and end date, delimited by milestones in the master schedule. Phases comprise one or several processes. Each **process** involves multiple trades, each of whom performs one or several **steps**, that is, the process sequence of steps forms a Parade of Trades (Tommelein et al. 1999).

Each trade performs **operations** defined by the sequence of steps they must take to complete their work (e.g., assemble parts of a component and secure it in place). Steps of an operation thought of as being part of the same single process may be (1) performed consecutively in that process or (2) interwoven by steps of other operations. Alternatively, the production system's design may have some steps of an operation in one process and other steps of the same operation in another process. Defining the steps of an operation and their relationship to processes is done during a comprehensive planning effort termed **work structuring** (Ballard 1999, Ballard et al. 2001, Tsao et al. 2004).

The objectives of work structuring may include to (1) Have trades work in a way they prefer, (2) Aim for constant crew size and continuous workflow (i.e., no work interruptions) (Ballard and Tommelein 1999), (3) Avoid trade stacking (i.e., only one trade works in any one zone at any time), (4) Use timely handoffs between trades, and (5) Balance the whole while pushing for speed.

To illustrate, Figure 2 depicts 9 steps of a process that starts with the milestone OVERHEAD SIGN-OFF (i.e., the completion of a preceding process) and ends with the milestone CORRIDOR SIGN-OFF. Each step shown by a color-coded square reflects the trade in charge of doing that work. Some trades perform multiple steps in the process (e.g., the trade CEILING TILE & GRID trade performs three steps). Steps are sequenced based on precedence requirements; some are shown concurrent with others because their sequencing can be decided later either way (e.g., ELECTRICAL Set fixtures can be done before MECHANICAL Set diffusers, or the other way around).

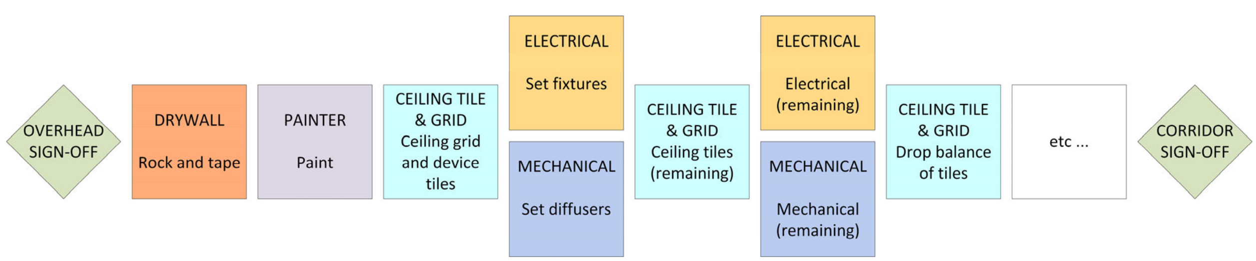

Figure 2: Process map of work in corridor, following overhead sign-off (derived from Figure 8 in Luktuke 2019)

Based on this framing and terminology, the WDM can now be specified.

WORK DENSITY METHOD (WDM)

SPECIFICATION OF THE WORK DENSITY METHOD (WDM)

Gericke et al. (2017) suggested that a method be specified at multiple levels namely by (1) Scope, (2) Coverage within the scope, and (3) Benefits expected from the method. The WDM is based on

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units of work density (defined in the next section). The scope of the WDM is process planning. Regarding coverage, steps that make up a process may pertain to work of any kind, repetitive or not. With work density serving as the building block for planning at a level of abstraction where only space and time matter, all other specifics of the domain have been abstracted out, that is, the project could be a healthcare facility, a school, a multi-story building, or a facility of any other type. Application of the method does not require intricate component-level detail nor explicit construction method descriptions; likewise, it does not require an a-prior defined top-down breakdown of scope of work or locations. "Require" is the operative word here: if such detail, descriptions, or a breakdown are available, they can be considered. The WDM operates on processes and is therefore situated in-between the levels of abstraction of project planning (development of the master schedule) and production planning (development of the lookahead- and weekly work plan).

The WDM determines for all steps in a process when to perform them and where, with space modeled in two dimensions. The objective of the WDM is to create one-piece process flow based on space use by zone, with the handoff being a zone and occurring at specified points in time. The resulting benefits are that the plan, thanks to its simplicity and regularity, is easy for everyone involved to understand, execute, and control.

Definition of Work Density

How much time a trade needs to perform the work in their process step depends on the project's specifics and management decision making by the relevant parties. It includes asking production system design questions such as: *What scope is included in any one step? Who will do it? Where is that work located? What means-and-methods will be used? How many resources will be deployed?*

To describe the duration of a step, Tommelein (Dunnebier et al. 2014, Tommelein 2017) coined the term work density, expressed as a unit of time per unit of area (e.g., in construction, the dimensional units may be hours/m^2 or days/m^2). It is a trade-specific project characteristic that compiles the outcomes of a many production system design decisions.

Work density is defined as the time a trade will require to do their work in a certain area, based on:

1. Product design (i.e., What is shown in the construction project drawings and specifications?),
2. Scope of the trade's work (i.e., Where are the trade jurisdictional boundaries and contractual agreements?),
3. Specific steps of the operation in their schedule (depending on work already in place and work that will follow later in the same or another process),
4. Means and methods the trade will use (i.e., How will work be done? E.g., increasing prefabrication off-site will tend to lower the work density on-site.),
5. Accounting for crew capabilities and size (i.e., Who will do the work? What are their skills, levels of technical understanding, etc.?).

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Increases or decreases in work density will result from using the corresponding production system design "throttles" (Binninger et al. (2017b) refers to "adjustment mechanisms") which are widely used in other planning methods as well, namely: (1) Modifications to product- and component characteristics, (2) Use of alternative breakdowns of the scope of work, (3) Resequencing of work and addition or removal of work from a process sequence, (4) Selection of alternative means and methods used by a trade, and (5) Worker- and crew trade skill particulars and the number of trade resources that can be assigned.

Work density is a metric that concerns all trades. It is an expression pertaining to workload and characterizes at what speed a trade's work is expected to progress through space. It is akin to cycle time but the novelty is that it augments that concept by explicitly referencing where work takes place with space modeled in two dimensions.

Steps expressed in units of work density lie at the heart of the new process-based planning method that is presented here. This step-based expression of time and space needed by each trade clearly demarcates handoffs between trades. It omits detailed characteristics of the work to be done, instead relying on trade specialists jointly with the project team to remove constraints as part of the make-ready function in lookahead planning. This expression also leaves out general characteristics such as finish-to-start relationships: these do not need to be shown explicitly because one-piece flow implies that process steps will succeed one another in space and time.

It should not be surprising that the WDM was invented and piloted in a collaborative-planning setting (Frandson and Tommelein 2014, Dunnebier et al. 2014). Trade specialists will know the availability, skills, and know-how of their individual crew members. They will know their company's procurement, fabrication, and supply practices, as well as tool and equipment setup and operation requirements, and they will be aware of project logistics- and site layout constraints. The trades' buy-in and commitment to the planning process and their agreement to adhere to the resulting plan are crucial to success; so is their willingness to share work density data.

Obtaining Work Density Data

Certain types of construction data used in planning or estimating (e.g., for determining activity durations based on product- and means-and-methods characterizations) have been systematically organized and codified over many years and are available nowadays in handbooks and computer programs (e.g., RSMeans 2021). That is not yet the case for work density data. Work density is a relatively new concept. It encapsulates many choices made by project team members as they individually and collectively design their production systems. This type of production data is in short supply (Ward and McElwee 2007, Binninger et al. 2018) and at this time still needs to be acquired more-or-less from scratch.

Two approaches for obtaining work density data are presented next. The approach selected depends on when the data is collected and, at that time, what project management- and production strategies have already been decided. Furthermore, the selection depends on whether one has access to those who will be doing the work and can make reliable promises about how work is intended to proceed.

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Approach 1: Color-up Floor Plans to Visualize Work Density Data

One approach is to meet with those who will be doing the work (e.g., the trades' crew leaders), have them articulate how they see their scope of work and plan to approach it, and what alternatives they consider feasible. To describe their workflow, they should color-up their trade-specific plans to show where they will be working day-by-day or in 2- or several-days' worth of work (e.g., Figures 1 and 2 in Frandson et al. 2013 and Figures 2 and 3 in Frandson and Tommelein 2014). A grid can then be superimposed on those color-ups to determine the work density by grid cell. For example, if a line showing 2-days' worth of work falls into one cell, the work density for that cell would be two days; if the same line were to extend equally over three cells, the work density for each of these cells would be prorated based on overlap and be 1/3rd of 2 days.

Approach 2: Use Production Data to Compute Work Density

When work density data is to be obtained at a time when trade specialists are not yet available, then an alternative to creating color-ups is to start with a quantity take-off using project documents and supplement that data with trade production rates and other construction know-how (e.g., need for space possibly situated away from the final installation location to stage and prepare materials). Such data will be more readily obtainable if those involved in planning can rely on experience doing similar work (e.g., Binninger et al. 2018). A grid must then be defined to determine each trade step's work density by grid cell. Some know-how remains to be developed in this area, e.g., to decide how to allocate the work density pertaining to a component that spans across a cell boundary (e.g., Singh et al. 2020 describe an approach and considerations).

In either case, given the scope of each step in the process being planned, the WDM requires that work density data be represented using a grid that covers the work space.

Use of Work Density Data

Work density data is required as input for the work density method. When dividing a work space into so-called **zones**, the time needed by a trade to complete their work pertaining to a given step in a given zone is computed by adding the values of the trade's corresponding work density in each grid cell within the zone. This cumulative work density is called the **workload** and is expressed as a unit of time per zone it pertains to.

Dividing a work space into zones is a common industry practice. For example, a superintendent may divide a large floor into halves for activities to take place concurrently in each one. However, this common practice can be somewhat arbitrary, e.g., when these halves are chosen to be equal in area it is unlikely that the trades' workloads in each half will be exactly equal but instead some trade will need more time than others to complete their work. This is because the choice is not informed by what actual work is to be performed by whom, where, and when, or does not reflect trade capabilities and preferences. The latter information is captured by means of work density that can therefore help create a plan that is more balanced from a workload perspective.

Steps of the Work Density Method

The WDM iterates through the following steps to create a process plan (Figure 3). Illustrations and examples follow.

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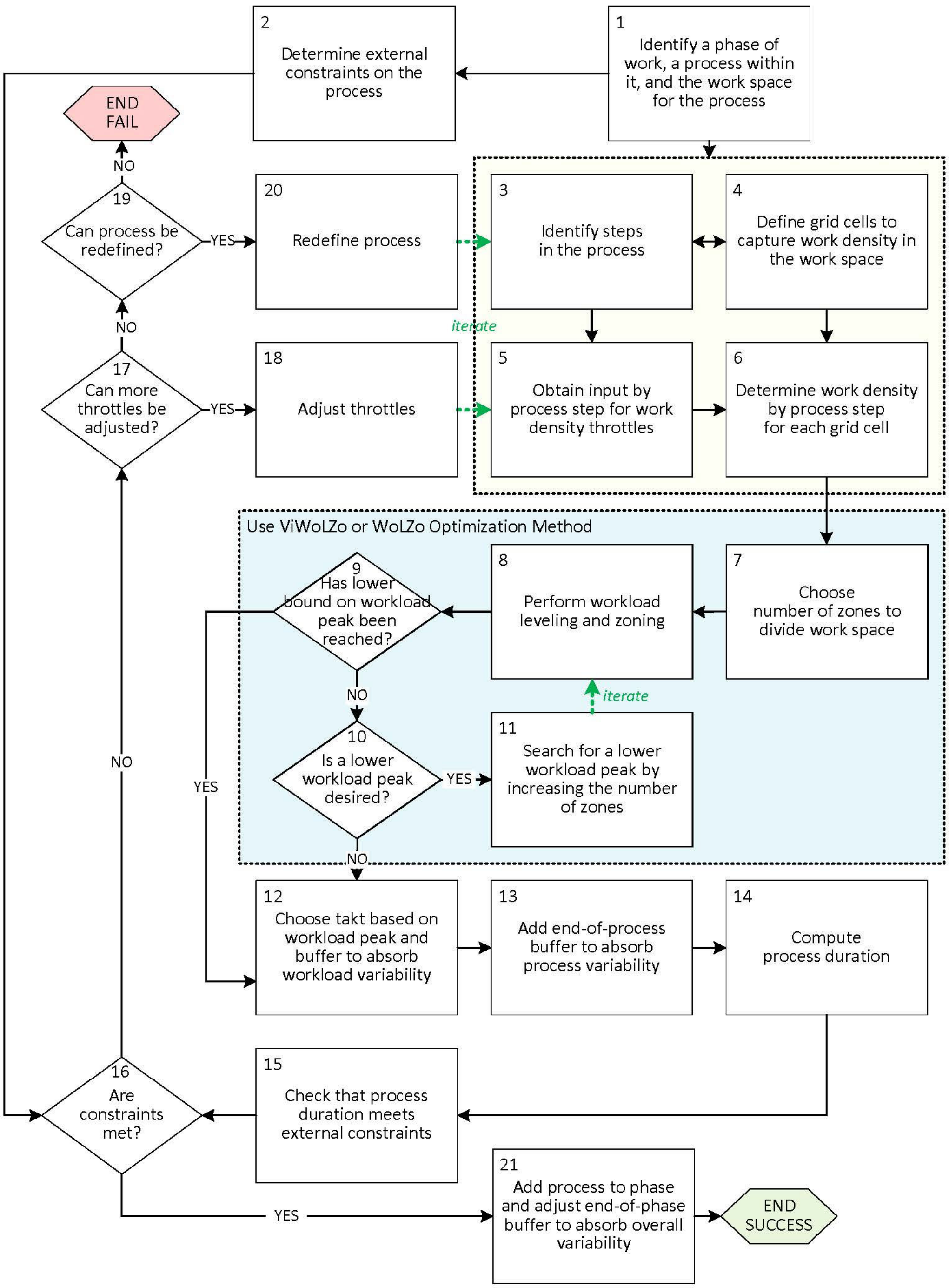

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378 Figure 3: Procedural steps of the Work Density Method

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1. Identify a phase of work, a process within that phase, and the work space for that process (e.g., "rough-in the corridor on level 5").
2. Determine the external constraints on the process (e.g., start and end dates).
3. Identify trades and their steps in the process including work steps, inspection steps, etc.
4. Define grid cells to capture work density in the work space where the process takes place.
5. Obtain input by process step for work density throttles, including scope, means and methods, crew size, etc. possibly using approaches 1 or 2 previously mentioned.
6. Determine work density by process step for each grid cell.
7. Choose number of zones to divide work space.
8. Perform Workload Leveling and Zoning: decide which cells belong to which zone, with zones being mutually exclusive and collectively exhaustive, while minimizing the workload peak across all steps in the process. Identify the peak(s) in the workload histogram. This may be done by hand using ViWoLZo (Singh et al. 2020) or using an optimization algorithm such as WoLZo (Jabbari et al. 2020).
9. Has the lower bound on the workload peak been reached? If YES go to 12. If NO go to 10.
10. Is a lower workload peak desired? If YES go to 11. If NO go to 12.
11. Search for a lower workload peak by increasing the number of zones. Iterate: go back to 8.
12. Choose takt based on workload peak and buffer to absorb workload variability.
13. Add end-of-process buffer to absorb process variability (e.g., potential rework).
14. Compute the process duration.
15. Check that the process duration meets all external constraints.
16. Are constraints (identified in 2) met? If YES go to 21. If NO go to 17.
17. Are there more work density throttles to adjust? If YES go to 18. If NO go to 19.
18. Adjust throttles to lower the work density in any one or several cells. Iterate: go back to 5.
19. Can the process be redefined (e.g., split steps, combine steps, add steps, or remove steps from the process)? If YES go to 20. If NO you are out of options; there is no solution.
20. Redefine the process. Iterate: go back to 3.
21. Add process to phase and adjust end-of-phase buffer to absorb overall variability.

WORK DENSITY METHOD APPLIED TO EXAMPLE PLANNING PROBLEM

The use of the WDM is illustrated next by means of examples. These examples are very simple so that the reader can easily check all calculations. For the WDM to be practical on real projects the calculations must be automated (e.g., Singh et al. 2020).

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Consider planning the process shown in Figure 4 that involves three trade partners, each performing a certain scope of work step-by-step and working consecutively. Figure 5 depicts the work density map for each trade's step by showing how many time units the trade will need to complete their scope of work in each grid cell.

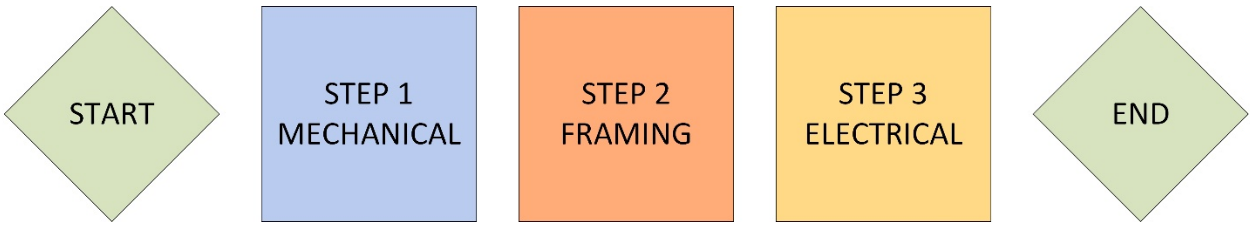

Figure 4: Process with three steps (S = 3)

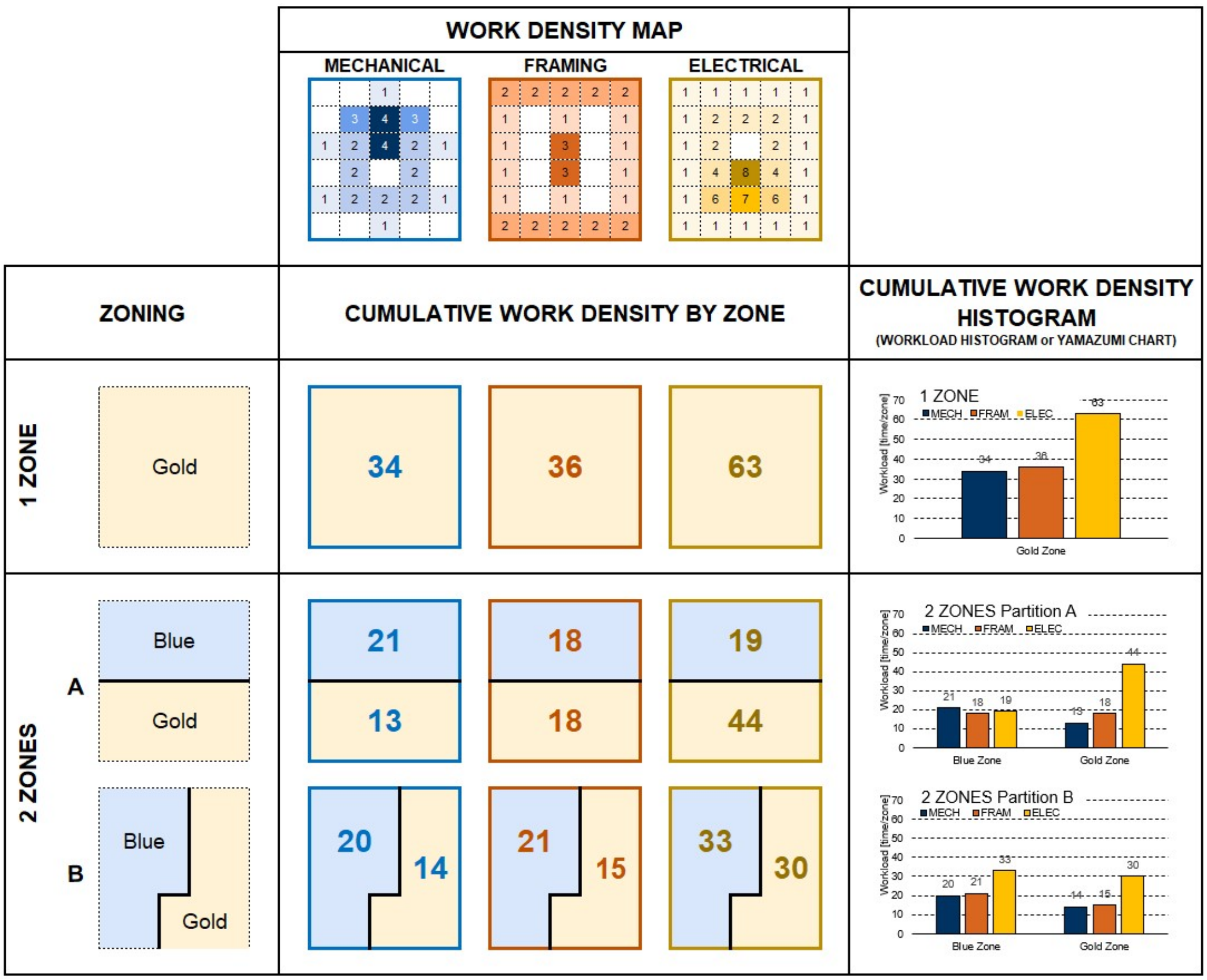

Figure 5: Work density maps and cumulative work density histograms of process with three steps (S = 3) and work space partitioned into one zone (Z = 1) and two zones (Z = 2) (after Figures 4 and 5 in Tommelein 2017)

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When **Z = 1** the entire work space is treated as a single zone. The workload (cumulative work density) of each process step is computed by summing up the work densities of the cells of that step's work density map that lie within the zone. This yields 34 for MECHANICAL, 36 for FRAMING, and 63 for ELECTRICAL as shown in the row 1 ZONE in the middle of Figure 5. As is commonly the case, the steps' workloads are imbalanced. This is shown in the workload histogram (also referred to as a cycle time- or Yamazumi chart) in the row 1 ZONE at the right of Figure 5. When setting T(Z) equal to the duration of the longest step in the process (the workload peak), namely the ELECTRICAL workload of 63, and allowing each trade the same time, the duration per Equation 1 is $D = (S + Z - 1) * T(Z) = (3 + 1 - 1) * 63 = 3 * 63 = 189$.

When treating the entire work space as a single zone it is arguable whether takting the process (allowing T(Z) to complete each step) is beneficial because doing so comes with a duration penalty. Instead scheduling the consecutive steps at their work density durations in the CPM-way, the duration is only $D = 34 + 36 + 63 = 133$. This CPM duration of the process is always shorter than the takted duration, however the takt approach and the WDM are beneficial when increasing concurrency without stacking trades as is demonstrated next.

When **Z = 2** the process can speed up. Consideration is now given to dividing the work space into two zones so that work can proceed concurrently without trade stacking. What should these zones look like and, once a certain zoning is selected, what is the duration?

In theory, if work density were uniformly distributed in the work space, then the workload peak for each half would be $63/2 = 31.5$ resulting in a duration $D = (3 + 2 - 1) * 31.5 = 126$. In reality and as the maps show, work density may not be uniformly distributed. Considering the trade with the largest workload, namely ELECTRICAL, the most even workload one can obtain is 32 in one zone and 31 in the other zone. The duration for the process then would be $D = (3 + 2 - 1) * 32 = 128$.

Figure 5 illustrates some alternatives. Partition A shows the work space divided in equal halves area-wise. The resulting workload histogram (right-hand side of Figure 5) peaks at 44. The duration for the process then is $D = (3 + 2 - 1) * 44 = 176$. Partition B shows the work space divided in unequal halves. The resulting workload peaks at 33 and the duration is $D = (3 + 2 - 1) * 33 = 132$.

Many other partitions exist with Z = 2, some of which achieve the aforementioned D = 128. We leave it to the reader to explore these.

The two-dimensional visualization of work density helps planners decide on changes in process duration or other plan improvements. Planners may want to lower workload peaks if a shorter duration is desired or to raise workloads that are not yet peaks if the duration is acceptable but a better balance of workloads within and across trades is desired. In any case, they can throttle work density by following the steps of the WDM (Figure 3). This throttling is the two-dimensional equivalent of line balancing of assembly lines in manufacturing (more on assembly line balancing, e.g., in Chapter 8 in Baudin 2002). The following examples show the use of work density throttles.

Throttle Crew Size: If the ELECTRICAL crew can be doubled and assuming a proportional change in work density, then the work density in the Blue Zone of Partition A becomes 10 (half of 19, rounded up) and in the Gold Zone 22. By speeding up the ELECTRICAL work in this way, the duration is $D = (3 + 2 - 1) * 22 = 88$.

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However, increasing the number of people in a crew all working in the same zone may cause overmanning that results in inefficiencies and loss of productivity. Assuming that enough crew members are available but avoiding overmanning, speed can be gained by breaking the ELECTRICAL step into two distinct sequential process steps, each one given the time $T(Z)$ to complete their work in a zone. With the additional step ($S = 4$) the duration of the process now is $D = (4 + 2 - 1) * 22 = 110$.

Throttle Means and Methods: A shorter duration may be obtainable by changing means and methods such as prefabricating assemblies. Presumably ELECTRICAL will need less time to install assemblies in a zone than they would building everything in place.

If it were possible to apply throttles so that the ELECTRICAL trade in Gold Zone of Partition A could meet or beat a workload of target of 21, with 21 being the workload peak for all other zones and trades, then the duration of the process could be as low as $D = (3 + 2 - 1) * 21 = 84$.

Throttle Scope of Step: Eyeing this target, if 23 units of work density can be removed from the scope in the ELECTRICAL step in the Gold Zone, then ELECTRICAL's remaining workload is $44 - 23 = 21$. Perhaps this scope could comprise scope of the cells with work density 8, 7, 6, and an additional 2 units of work density from another cell in that zone.

Subsequently, if it is feasible to complete work removed from the process step without adding to the total duration (e.g., during a second shift), then all work together will have duration $D = 84$. If removed work is completed off-takt either before or after the process itself, then all work together will have duration $D = 84 + 23 = 107$.

This example explained how work density maps and throttles can be used to generate process plans of various durations to meet milestone dates. The following sections highlight noteworthy observations pertaining to the WDM.

WORK DENSITY GRID VS. LOWER BOUND ON WORKLOAD PEAK

Step 4 of the WDM states the need to define a grid but does not specify how. For example, what are the advantages of making the grid mesh coarse or fine? This question matters because the design of the grid with work density data affects the solutions that can be generated. Choosing a finer- rather than a coarser grid results in more cells for which to collect work density data. This is likely to demand more effort especially when work density is unevenly distributed in space, but the trade-off is that a finer grid allows for more zoning alternatives.

Figure 6 illustrates this point (compared with Figure 5 that showed the entire workload histogram for a given zoning, the right-hand column of Figure 6 shows only the workload peak). The scenarios comprise work density maps for trade Q and R, respectively WD(Q) and WD(R), but their grid varies from 1-by-1 wide-and-high in Scenario 1, to 2-by-1 in Scenario 2, and 2-by-2 in Scenario 3. Scenario 3 will illustrate the caveat mentioned earlier.

Scenario 1 allows for only a single zoning alternative. With $T(Z) = 14$ the duration is $D = (2 + 1 – 1) * 14 = 28$.

Scenario 2 allows for two zoning alternatives, one for $Z = 1$ where $T(Z) = 14$ and one for $Z = 2$ where $T(Z) = 9$. With $T(Z) = 9$ the duration is $D = (2 + 2 – 1) * 9 = 27$.

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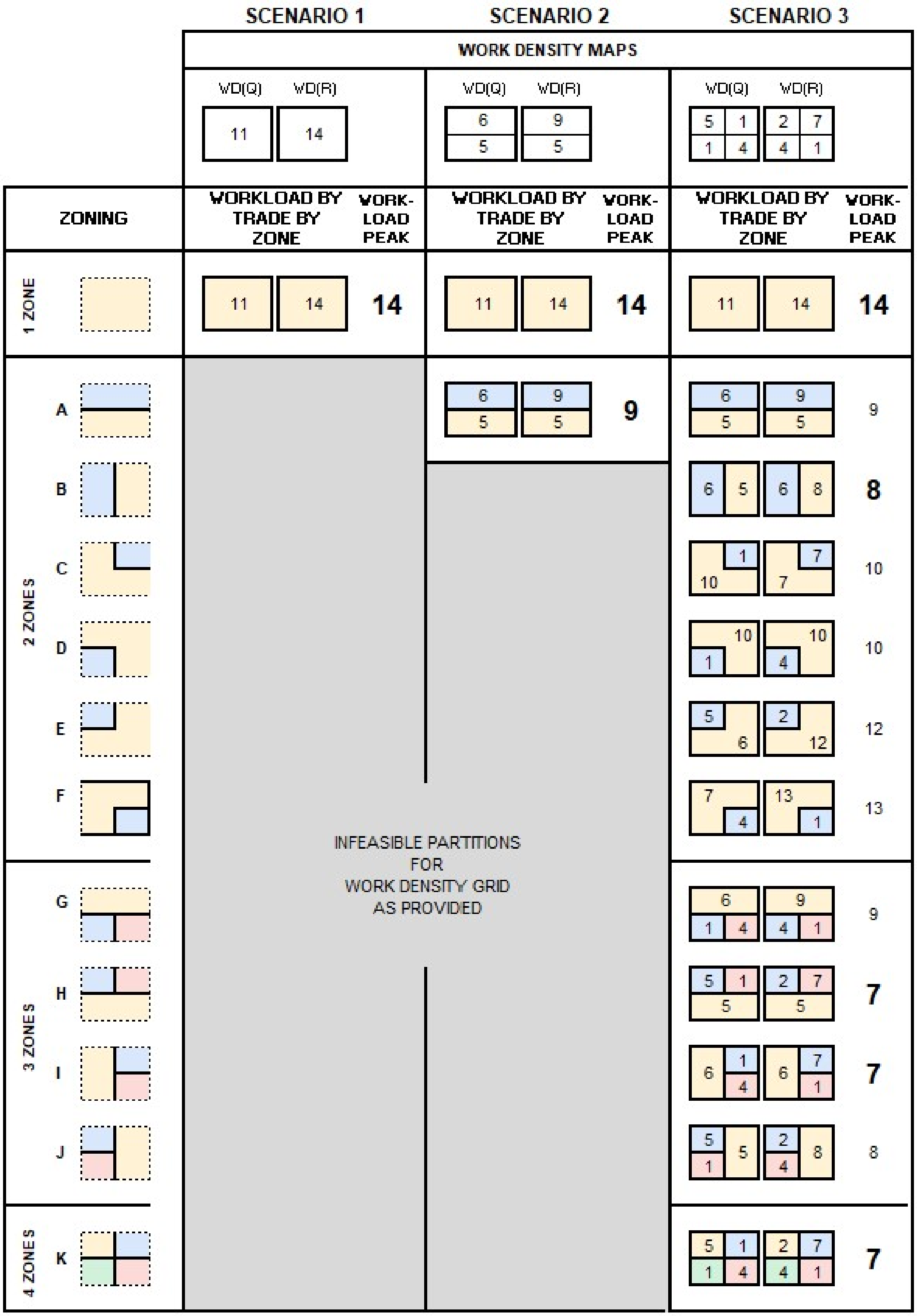

Figure 6: Coarseness of work density grid vs. zoning and workload peak T(Z) alternatives

Scenario 3 allows for a total of 12 zoning alternatives: one partition for Z = 1, six partitions for Z = 2 (Partitions A through F), four partitions for Z = 3 (Partitions G through J), and one partition for Z = 4 (Partition K). While Partition A in Scenarios 2 and 3 is the same, now Partition B is preferred since it achieves the lowest value 8 of the workload peak of any of the steps in any of the zones. With T(Z) = 8 the duration is D = 24.

The caveat is that as Z increases to allow for increased concurrency it is not always the case that T(Z) and D decrease. In Scenario 3, indeed, T(Z) decreases from 14 for Z = 1, to 8 for Z = 2, but then remains constant at 7 (Partitions H and I for Z = 3, and Partition K for Z = 4) when Z further increases. Consequently, increasing Z now results in a longer duration: for Z = 3 the duration is D = (2 + 3 – 1) * 7 = 28 and for Z = 4 it is D = (2 + 4 – 1) * 7 = 35.

This is explained as follows. Because the largest work density in any cell of WD(Q) and WD(R) is 7, any zone that comprises this cell will have a cumulative work density of at least 7. In general, not a single- but multiple steps may have the same limiting value in their work density map. This value defines a lower bound on the workload peak. Given Equation 1 with the number of steps S being constant, once T(Z) reaches that limit, the duration will increase with Z.

The reader can sharpen their intuition by imaging a situation where a certain scope of work is concentrated in a small area, namely an area so small that dividing it into parts would make it impossible to do any work in any of the parts (i.e., the grid cannot be refined further). Perhaps this was the case for the work density value 7 shown the upper-right grid cell of WD(R) in Scenario 3. It is logical that the nature of the work is bound to constrain the work density in any grid cell, possible zoning alternatives, and thus T(Z). So while one might think that increased concurrency will result in a shorter process duration, there is a limit.

WORKLOAD PEAK PARADOX

A detailed look at the use of work density sheds light on an opportunity, perhaps counterintuitive, for zoning the work space and thus for planning the work. Returning to fundamentals, a process that is planned by means of takt is akin to a line-flow system and all such systems have bottlenecks. Loosely defined, a bottleneck is a "stage [step] in a production system that has the largest effect on slowing down or stopping the entire system" (Roser et al. 2002 p. 1079) and "The bottleneck rate of a line is the rate (parts per unit time or jobs per unit time) of the workstation having the highest long-term utilization" (Hopp and Spearman 2011 p. 231). The presence of a bottleneck is always of concern because it chokes the system's throughput. The question is: What and where is the bottleneck in the system?

It is common in a line-flow system to identify the bottleneck station and, likewise, in a construction process to speak of a bottleneck trade. In "The Goal" (Goldratt and Cox 1986) the bottleneck is Herbie, the slowest hiker in the boy-scout troop. An example in construction is perhaps the electrician who needs a lot of time to complete all work in areas with complex, dense wiring, but beware of overgeneralization.

Although the tendency is to speak of "the" bottleneck and to presume that one can be singled out, a process could have multiple bottlenecks at the same time. In systems subject to randomness the bottleneck is, in fact, not always located at the same station(s) but can shift from one station to another over time (e.g., Roser et al. 2002). Both phenomena occur in construction settings as well. Both are handled in the WDM. The former would manifest itself when for a given zoning more

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than one step in a process has a workload equal to the workload peak. The dynamics of the latter is addressed by the selection of a fixed time T(Z) within which all process steps must be performed.

Figure 7 illustrates the point to be made about bottlenecks when work density is considered (note that Scenario 3 is identical to Scenario 3 in Figure 6 for Z = 1 and 2).

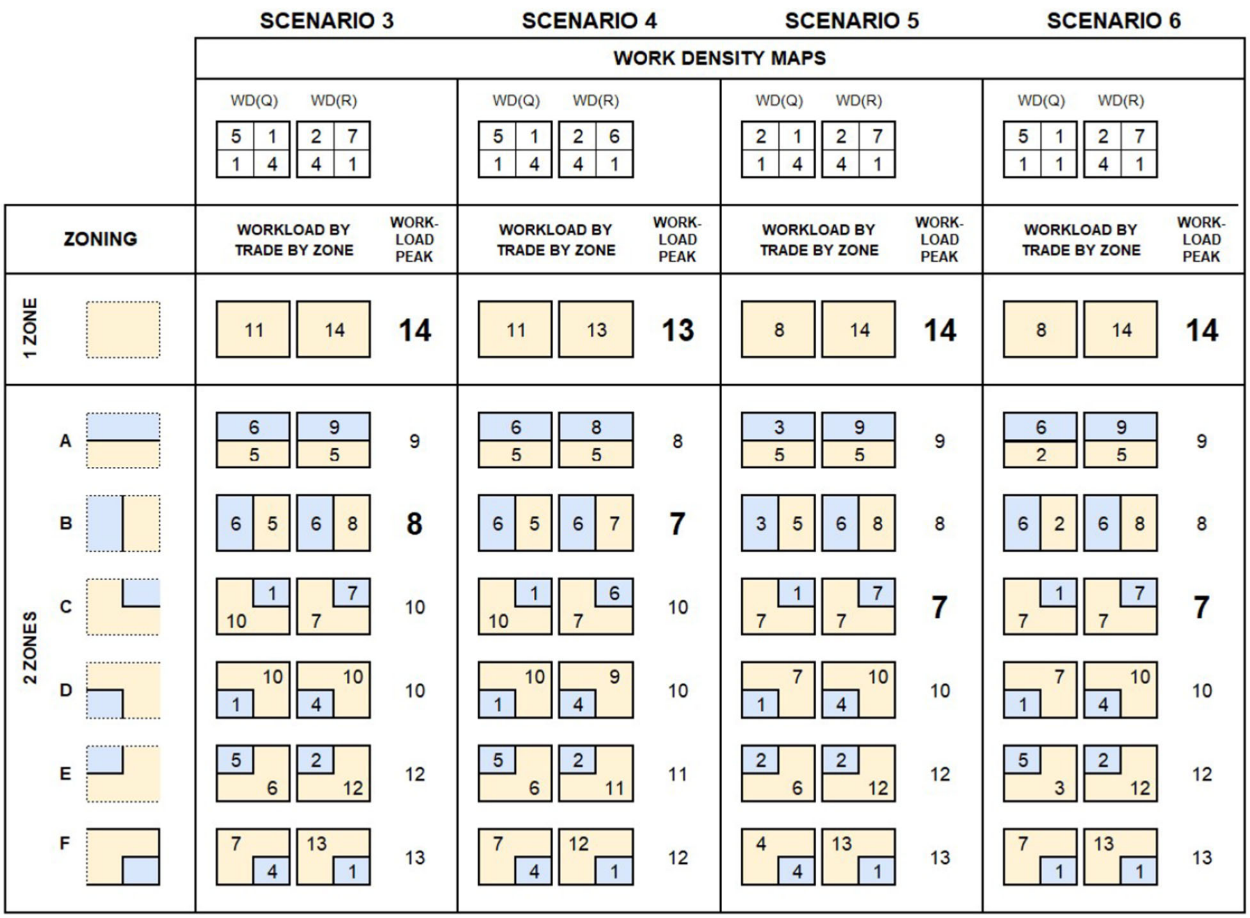

Figure 7: Reduction in work density of workload-peak step (Scenario 3 vs. Scenario 4) or other step (Scenario 3 vs. 5 and 3 vs. 6) allows for rezoning to lower workload peak T(Z)

Now assume that the customer requires a duration of 22 or less. To meet this requirement, using Equation 1 and given values for D, S, and Z, the value of T(Z) can be calculated. For Z = 2, T(Z) must be lowered to 7 or less in order to yield a process duration D = 21 or less. Since Scenario 3 presented all possible partitions for Z = 1 or 2 and the corresponding durations are always too long, other work density throttles must be leveraged to redesign the process. What options does the project team have to achieve this requirement?

Since Step R had the highest workload for Scenario 3 and Z = 1, it is tempting to call it the bottleneck and force the trade involved to lower its work density. In fact, Step R also defined the workload peak for Partitions A, B, D, E, and F. It is easy to label the trade responsible for this step as the bottleneck trade, however doing so is narrow minded. Lowering Step R's work density is one- but it may not be the only option to lower the workload peak. The narrow-mindedness of singling out a trade as the bottleneck trade is illustrated in Figure 7 Scenarios 4, 5, and 6.

Scenario 4 presents perhaps the intuitively most obvious option for process redesign. Lowering R's work density lowers the process duration; in general, should the process include multiple steps with the same workload peak, then all peaks must be lowered simultaneously for the duration to be lowered. Lowering the work density in R's upper-right cell from 7 down to 6, for Z = 1 results in a T(Z) = 13. This is lower than it was but not useful because the duration computed with that value still does not meet the requirement. For Z = 2 and Partition B, it results in a T(Z) = 7; this meets the requirement. (Readers may ascertain themselves that if further division of the work space were deemed feasible, then some partitions for Z = 3 or Z = 4 result in an even lower T(Z) = 6, but the duration does not shorten.)

Scenario 5 presents another option for process redesign. A change to the work density map of Step Q while leaving the work density map of Step R untouched can also achieve the desired result! By lowering the work density in Step Q's upper-left cell from 5 down to 2, for Z = 2 and Partition C this results in a T(Z) = 7 which meets the requirement. Likewise, Scenario 6 illustrates that lowering the work density in Step Q's lower-right cell from 4 down to 1, for Z = 2 and Partition C this likewise results in a T(Z) = 7. This paradoxical situation occurs for Partition C for which, it is noted, in Scenario 3 Step Q's maximum workload was greater in value than Step R's (10 vs. 7). The process duration can therefore be shortened by lowering that maximum value T(Z) to be equal or less than the maximum of Step R's.

Additional options for process redesign are to lower the work density of multiple cells in a single work density map at the same time possibly even down to the value 0 (e.g., performing work elsewhere), or to lower the work density multiple cells in different work density maps (i.e., multiple steps simultaneously).

Scenarios 5 and 6 illustrate the so-called **workload peak paradox**. The paradox is that for a given Z, the step of the trade that determines the workload peak for a given zoning of the work space, will not necessarily be the one that determines the workload peak when other zoning alternatives are considered. Correspondingly, the workload peak of zoning alternatives can possibly be lowered by lowering the work density of any step in the process. This is to say that calling a trade (or a company) the bottleneck trade ignores the specifics of the process steps relative to one another.

DISCUSSION

WORK DENSITY CONCEPT

Work density as defined in this paper is a new concept with a unique meaning. It conforms to a general understanding of density, the mathematical definition of which is "the quantity per unit of volume, unit of area, or unit of length" (Merriam-Webster 2021). Work density is a term that appears to resonate well with construction practitioners. Since we first presented the concept in public (Dunnebier et al. 2014) we increasingly hear work density used in conversations among project personnel. A challenge is now that the WDM definition of work density may be confused with uses of the same or related concepts in the construction planning and scheduling context. Several such concepts are described next.

Aiming to attain an ideal level of space utilization Morkos (2014) developed the Tri-Constraint Method (TCM). TCM generates schedules with a short duration that maximize so-called work density and eliminate spatial clashes that may arise when maximizing space utilization. His use of work density derives from a Cartesian coordinate representation of minimum work space required by crews acting on product components depicted in a BIM (e.g., Akinci et al. 2002). It relates to the Average Space Utilization Factor (ASUF) a metric that gauges the degree to which the entire site space is occupied. In contrast, the WDM relies on the notion of sufficiency of space provided to trades to do their work in a zone for a certain duration, and work does not have to be directly tied to the final installation location of components. Sufficient space will likely be larger than TCM's minimum space. Moreover, in the WDM all available work space (a well-defined subset of the entire site space) gets allocated to one zone or another. Rather than maximize work density, the WDM aims to lower the workload peak in a process.

In regard to other uses of density, the Chartered Institute of Building (2011) refers to "increasing schedule density" as the process of adding levels of detail to the schedule over time as better and more certain information becomes available. Finke (2000) and Ottesen and Hoshino (2014) use the term "schedule density" and "schedule activity density" to gauge the number of overlapping activities in a schedule specifically in the context of change and delay analysis for productivity loss claims. In contrast, the WDM is not specifically about increasing the number of people involved (though crew size is accounted for when using the production rate to compute work density) but rather how much time any trade (which could be any number of workers, perhaps zero if an autonomous robot is at work) must spend in a given area to complete the agreed-upon scope of work.

WDM vs. Other Planning Methods

The WDM takes as input milestones and scopes of work identified at a higher, more abstract level of planning, namely in the master schedule where CPM plays a role. Processes planned by means of the WDM in turn feed lower-level planning efforts. Work in each step needs to be made ready in the lookahead planning process prior to being selected for inclusion in a commitment plan or weekly workplan for execution.

The WDM with its process-planning focus is used at the level of phase planning. It is at that level and using methods such as pull planning that trades refine their own production strategies including logistics and the use of shared resources. This is now possible as they have ascertained when and where they will be working, who comes before and after them (hand-offs to receive and make), and they know their work will not be hampered due to trade stacking.

Phase planning is best done when trades have been onboarded and they can speak to the work they have to complete, that is, they can meaningfully quantify the work densities of their steps. As the phase plan and within it one or several process plans take shape, trades may be amenable to some give-and-take by throttling the scope of their steps, crew sizing, or means and methods in order to help lower their work density in certain areas (cells in their work density map) where such investments prove to be beneficial at the process level. They also may find ways to beneficially increase their work density without jeopardizing the workload peak. The project team can invest and provide incentives to lower the workload peak(s) in a process so that all steps will be able to proceed faster. For this reason and with such a systemic approach in mind, the WDM was first envisioned for use in collaborative planning (Tommelein 2017). Phase- and process planning should enable all involved trades to commit to the team's overall production approach, i.e., they buy into the (takt) plan.

The work density data required for the WDM can also be used in other planning methods that likewise aim for activities to take place concurrently yet not share space, i.e., methods that avoid trade stacking. By using work density as input, such planning methods can be constructive in nature and guarantee to meet that objective, rather than be improvement-based namely having to rely on ad-hoc space conflict (clash) detection.

Resource Considerations

The WDM aims to create a swift process workflow with resources ready to complete each step. It does so at the expense of resource utilization as is clear from the workload histograms (Figure 5). In fact, some degree of resource underloading (use at less than 100% capacity) is desired to ensure buffer capacity, in case of need, to ascertain no step duration will exceed the workload peak. The percentage of underloading and the cost thereof will vary case by case, but the argument is made that this investment is paid back by avoiding cascading delays in the schedule and by providing a setting in which trade crews can improve their process capability for doing certain work (Tommelein 2020).

When the WDM is applied to repetitive work, it may be possible to ensure continuity of some resources across zones to avoid interruptions and ensure high utilization. However, some resources are expected to not be deployed optimally. When work is non-repetitive, the work a trade performs during their step can vary significantly from one zone to the next. Some resource continuity may still be achievable but, in any case, flexibility is essential, e.g., workers must be skilled to perform many types of work and the supply of materials and tools must match what is needed zone by zone. Flexibility is perhaps even more important at the process level during give-and-take discussions, as mentioned, than it is at the step-level.

Design of Work Density Grid

In contrast to location-based methods that require a priori definition of a LBS or takt planning methods that start by identifying SSUs, the WDM uses work density data to generate the zones where work defined as process steps is to take place. These zones can vary significantly in terms of their shape and size. They are process specific and will likely vary from one process to another. An open question is: What are the tradeoffs between using a single zoning throughout a project vs. changing zonings from one process to the next?

The applicability of the WDM does not depend on how the grid is defined, but possible zonings (partitions) that can be generated do depend on it (Figure 6). Orthogonal grids have been used in the examples provided here but other tessellations are acceptable as well. An open question is: Exactly how to choose the grid of work densities? Grid spacing and grid cell boundary locations relative to the product design also matter. A grid may be evenly spaced or not, allowing cell boundaries to relate to architectural product features (e.g., line up with the middle vs. side of a hallway) (Singh et al. 2020). Furthermore, while the grid used by the WDM is defined only in topology (not geometry) the actual dimensions of the cells must be informed by the domain of application. Cells must be both large enough to allow for a trade to work—if perhaps not optimally—should partitioning of the work space yield a zone comprising only a single cell (e.g., a crew working on a scissor lift needs sufficient space to maneuver), and small enough so it will make sense to combine several into larger zones.

The selection of the grid used to represent work density data affects the solutions that can be generated. When the number of zones increases, the sizes of the zones will tend to become smaller until zones correspond to cells. The work space cannot be divided into more zones than the number of grid cells in the work density maps.

If a rationale can be applied to split cells into smaller ones so that the grid has more cells, then more zoning alternatives exist. To illustrate, Jabbari et al. (2020) divided cells of one grid evenly, assigning to each half-cell half of the cell's work density (in reality, work density in any cell may not divide up so evenly, as Binninger et al. (2018) illustrated). This converted a 6-by-9 grid into a 6-by-18 grid and when Z increased indeed resulted in finding lower values of T(Z). In general, as the work space gets divided into more zones (Z increases), it may be possible to find a lower workload peak T(Z) and thus reduce the duration D; however, lower values are not guaranteed (Figure 6 Scenario 3).

The workload peak paradox has significant implications in terms of how one approaches production planning with work space zoning. Perhaps work can be shifted from one cell to another (e.g., a floor-tile cutter may be set up at some distance from the work face) to lower T(Z). Judicious investment in logistics and off-site fabrication will likely result in a shorter duration if and only if indeed all trades in a process can keep pace. Strategic and operational planning conversations around what to speed up and where will revolve around the concept of work density.

COMPUTATIONAL METHODS FOR WORKLOAD LEVELING AND ZONING

In Figure 4 all zoning alternatives were enumerated but this example was exceptionally simple, based on a 2 x 2 grid. Grids of larger dimensions quickly render exhaustive enumeration and evaluation of all zoning alternatives infeasible. Mathematical optimization methods more elegant than exhaustive enumeration must therefore be developed for the WDM to be practical.

A challenge is that the process planning problem addressed by the WDM is difficult to solve. Even the subproblem identified as Workload Leveling and Zoning (WoLZo) in Step 8 of the WDM is difficult. The WoLZo problem as formulated by Jabbari et al. (2020) is proven to be NP-hard. Simply put, this means that the search for an optimal solution may take a very long time if one can be found at all, even despite the computing prowess at our disposal today. This notwithstanding, Jabbari et al. (2020) coded an elegant algorithm to find the optimal partition by enforcing shape constraints on zones (limiting them to only rectangles or L-shapes) and thereby demonstrated that novel mathematical approaches are within reach to solve these difficult problems. Further study is in order of other formulations.

CONCLUSIONS

Starting from theoretical underpinnings in Lean Construction recognizing that the combined pursuit of productivity and cycle time objectives requires trade-offs, the contribution of this paper is that it specified a new spatiotemporal planning method called the Work Density Method (WDM). The WDM provides a data-driven approach to support the kind of process-level planning that is typically done by superintendents. The novelty of the method is that it uses a granular work density grid to zone the work space while aiming to minimize workload peaks so as to instill process regularity in work that otherwise may be deemed non-repetitive. The WDM establishes one-piece process flow with the pieces being the trade's step-sized units of work that get done in one zone after another.

The elegance of the method is that it seeks to identify zoning alternatives that have lower workload peaks as expressed in units of work density, where work density is the common unit for planning repetitive as well as non-repetitive work. The flexibility obtained by throttling work densities and exploring alternative ways of partitioning the work space may result in seemingly paradoxical situations, but it is that flexibility that makes it possible to create better plans. A limitation of the method is that it requires work density data, specified by grid cell, which is not readily available at this time. The WDM also requires computational support when applied to planning problems of any size much larger than the examples provided in this paper.

This new framing of process-level planning certainly demands more in-depth theoretical study and further refinement in practice. Topics to study include work density data collection, grid definition, use of capacity- and other buffers, work structuring and process definition, desirability of changing zonings from one process to the next, optimization, and cost-related analyses.

DATA AVAILABILITY STATEMENT

All data, models, and code generated or used during the study appear in the submitted article.

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