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WORKLOAD LEVELING METRICS FOR LOCATION-BASED PROCESS DESIGN

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ABSTRACT

Process design can help to meet project deadlines and ensure a smooth workflow. While work structuring (WS) is commonly used to design processes as linear flows, doing so may not account for 2-dimensional spatial variation in work and such variation can disrupt the flow. To limit disruption, takt production and the Work Density Method (WDM) have been developed, but metrics are yet needed to gauge and visualize the quality of workloads to achieve the desired flow. This paper presents multiple perspectives to assess desired outcomes of workload leveling and formalizes them into optimization objectives. It proposes nine metrics, grouped into seven types, to measure the success of achieving these objectives. The value of these metrics is illustrated using XLWoLZo, an Excel-based tool with an off-the-shelf genetic algorithm (GA), to solve a toy problem. The paper compares XLWoLZo's results obtained with the suggested metrics to the results of the metric used in existing models, examines how the resulting values of metrics compare to one another, and assesses their impact on desired outcomes. The paper concludes that no single "best" metric exists and suggests combining metrics to balance conflicting objectives. Finally, the paper discusses limitations and offers future research directions.

KEYWORDS

Process, Location-based planning, Takt planning (TP), Flow, Variability

INTRODUCTION

Process design (aka. process planning) matters to scholars and practitioners engaged in work structuring (WS) and production system design (e.g., Ballard et al. 2001a, 2001b). The aim is for process- and operation design to be aligned with product design. WS includes designing the "chunks" of work to be assigned, deciding their sequence and their release from one production unit (PU) to the next with or without decoupling buffers, and scheduling when they are to be done. A work chunk is "a unit of work that can be handed off from one production unit to the next" and a PU is "an individual or group performing production tasks" (Tsao et al. 2000). Thus, process design includes deciding what steps to include in a process, determining what work to assign to each step and who will do what, sequencing steps, and defining handoffs between them. In addition, it includes deciding what- if any buffers are needed between processes.

WS is commonly used to define construction processes as linear sequences of steps, thereby abstracting them to resemble line flow systems (e.g., manufacturing assembly lines). This abstraction can also be useful when studying the flow of crews. However, construction processes have work that depends on the 2-dimensional (and 3-dimensional) spatial

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characteristics of the project. Ignoring spatial variation of work can affect the quality of the assumed linear flow.

Location-based methods including takt production (aka. takt- or takt-time planning and control) (e.g., Bulhões et al. 2005, Fiallo & Howell 2012, Frandson et al. 2013, 2014, Haghsheno et al. 2016, Lehtovaara et al. 2021, Tommelein 2017, Theis et al. 2017) emphasize concern for space use in production system design. In the planning part of takt production, the aim for process design is to designate zones (work areas or locations) on a construction site where crews will work successively, one at a time, and complete the work in their step within a fixed amount of time (called the takt). The desire to plan work in different zones to a takt is difficult to satisfy because the quantity and complexity of construction work, and consequently the time needed to do that work, tends to be distributed non-uniformly in space.

To characterize non-uniformity, location by location, of the time needed by trades to complete their work, Tommelein defined the concept "work density" and developed a planning method based on it, called the Work Density Method (WDM) (Dunnebier et al. 2014, Tommelein 2017). 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" (Tommelein 2022). The WDM describes a numerical way of zoning a workspace while minimizing the workload peak across zones and steps to meet the desired takt (Jabbari et al. 2020, Tommelein 2022). In contrast in this paper, we view workload leveling from multiple perspectives, not only that which aims to reduce the workload peak. We identify metrics that measure, describe, and visualize the "levelness" of a workload, and accordingly define workload leveling.

The next section of this paper reviews literature on process design specific to takt planning, flow, and the WDM, and literature on a problem that is somewhat similar to workload leveling, namely resource allocation and leveling for construction scheduling. The section thereafter introduces desired outcomes of process design and suggests metrics to be studied as performance indicators towards achieving these outcomes. A section on research implementation presents the computer-based tool developed using an off-the-shelf genetic algorithm (GA) to optimize a toy planning problem so that the results from the optimizations according to the suggested metrics can be evaluated and discussed. This paper concludes with recommendations for metrics to enhance process design methods and suggests future research.

LITERATURE REVIEW

TAKT PLANNING AND FLOW

Construction project management has traditionally focused on transformation at the activity level, ignoring handoffs between activities (Ballard and Howell 1998). In contrast, Koskela (2000) acknowledged that transformation-, flow-, and value views on production systems are complementary and must be considered together to improve production more holistically. Therefore, and among other things, flows must be identified and measured.

Given that most construction activities have varying durations and work spread out unevenly in space, it is difficult to identify workflow. Irregular and erratic workflow translate into incomplete work and untimely hand-off of space. Process design with workflow in mind must ensure that the scope of work is well defined by process step and location so that the assigned work can be completed and handed over within the allotted time. Spatial continuity and timely completion tend to reduce the share of non-value-adding activities and reduce the degree of control complexity (Alves and Formoso 2000).

The term workflow has been widely used in the Lean Construction literature, but different authors have used it to refer to different types of flows. Among them, Shingo (1986) described production in terms of two types of flow: process flow and operation flow. Processes represent what happens to raw materials (and pieces of information) as they flow through the project and become finished goods, with work done stepwise by different crews. Operations represent what people with tools and equipment (referred to as crews or production units) do to products. Tommelein et al. (2022) differentiated flows in construction from a location-based planning perspective while recognizing their two-dimensional nature. They defined process location flow as synonymous with process flow and trade location flow synonymous with trade flow.

Process flow determines how long it will take to get a product to the customer. This duration is called the process cycle time and it relates to the system's speed (aka. throughput rate). Since a process comprises steps of work performed by crews, the durations of these steps (the step cycle time or workload) define the throughput rate. An objective of production system design is to match its throughput rate to the customer's demand rate (Hopp and Spearman 2011). The maximum amount of time allowed for producing a product (supply rate) so that it will meet the customer's need is called the takt. Using takt planning, a process can be designed so that each step of work can be completed reliably within the allotted time by crews following each other sequentially while going from one zone to the next.

The literature on flow and methods for takt planning in construction (cited previously) highlight different perspectives on what is considered a good takt plan. They consider process flow as well as trade flow and other flows, and trade-offs between them. The WDM for example (described next) allows planners to objectively balance process flow with trade flow.

Work Density And Work Density Method (WDM)

To improve the quality of production plans (e.g., takt plans) in terms of achieving a shorter duration and higher workflow reliability, a goal is to reduce variability in the system. In construction processes this can be done by standardizing work, instilling regularity of work location and timing, and defining clear hand-offs between crews, thereby reducing the requisite amount of control and coordination between them.

Rather than zoning a work space by simply dividing space according to physical features of the structure being built, the WDM performs both workload leveling and zoning. The idea is to define zones so that number of work hours are similar for all steps of trades moving from one zone to the next (Frandson et al. 2013). Specifically, the WDM defines zones while minimizing the peak workload across all zones and all trades.

For a given work scope and trade crew working in a certain unit of space, and associated work structuring specifics, "work density" describes the unit of time the crew will need to complete that scope. Work density captures what work will be done, by whom, where, and how (Tommelein 2017). For projects with repeating architectural features in their product design (e.g., modular hotel rooms), planners can define Standard Space Units (SSUs) (Binninger et al. 2017) and repeated reliable handoffs of more-or-less similar workloads to be completed within a takt. Even for projects without such architectural features, i.e., where handoffs of similar workloads are not obvious, Jabbari et al. (2020), Singh et al. (2020), Diab and Tommelein (2020), and Tommelein (2022) were able to apply the WDM as the method takes as input a work density map for each step in a process. The map represents how much time the crew will need to complete their work across the work space, granularized cell by cell. Tommelein (2017) and Singh et al. (2020) detailed processes for creating work density maps.

The WDM supports process planning for a linear sequence of steps (a process) using a work density map for each step. Work space is divided into zones (that are mutually exclusive and collectively exhaustive) by assigning cells from work density maps to each zone. Then, step by step, the work densities of cells in each zone are added. The resulting cumulative work density, called the step cycle time or workload, describes the time a crew needs to complete their step-worth of work in the given zone.

The workload distribution across zones and steps visualized on a workload histogram or Yamazumi chart helps planners see if a given process design meets their desired outcome(s). If not, the planner may use various throttles (e.g., changing zone boundaries, modifying process steps, changing resources or means and methods available to the crew) to modify the plan. The characteristics that make for a desirable process plan can change with the situation and may require trade-offs. For example, a common trade-off in location-based methods involves reducing the time 'workers wait on work' (crew flow) versus 'work waiting on workers' (process flow) (Linnik et al. 2013).

RESOURCE LEVELING IN CONSTRUCTION PROJECTS

The workload leveling problem is similar to resource leveling and resource-constrained project-scheduling problems (RCPSPs). Resource allocation methods ensure that resources required for a plan do not exceed resource availability constraints (e.g., Colak et al. 2006, Davis 1974, Liu et al. 2005). Although in the basic RCPSP model reduction or minimization of the project duration remains the single most studied objective, several extensions of RCPSP consider other objectives or combinations thereof, such as variabilities in the project environment and resource capacity (Chakrabortty et al. 2017, Hartmann and Briskorn 2010).

Some resource leveling methods try to reduce fluctuations in the number of resources used, while others strive for continuous use of resources to improve productivity and reduce cost (e.g., El-Rayes and Jun 2009, Hegazy 1999). The mathematical formulation of these methods may use one or multiple objectives similar to workload leveling, i.e., to minimize resource fluctuations or lower resource peaks. Examples include the minimum moment method (Harris 1978), the PACK method (Harris 1990), the double moment method (Hegazy 1999), and the entropy maximization method (Christodoulou et al. 2010).

Since these methods are typically used in transformation-based optimization models (exemplified by the Critical Path Method (CPM)) (Brucker et al. 1999), the differences with flow-based process planning methods (exemplified by the WDM) must be highlighted. Resource allocation methods may prioritize critical activities over others when allocating resources. When multiple activities require the same resource, different methods may prioritize them differently. Resource leveling methods tend to prioritize the use of resources required for critical activities by scheduling those activities at their earliest possible time. They minimize resource fluctuations by shifting noncritical activities within their available float to keep the project duration of the original early schedule unchanged, if possible (El-Rayes and Jun 2009). In contrast, in takt planning, there is no prioritization for resource allocation or leveling as all activities (i.e., steps in a process) are critical. In that sense, steps within a process have no float. However, each step has a capacity buffer to ensure enough people on the crew are at the ready so that, in case work takes slightly longer than anticipated, they will be available and able to complete their step within the takt. In addition, takt plans include buffers between processes and at the end of processes. The judicious use of buffers prevents delays that could reverberate through the schedule (Dlouhy et al. 2019).

Flow-based planning methods are relatively new compared to the extensive body of knowledge that exists for transformation-based methods. A missing piece for their broader adoption pertains to metrics: there is a lack of metrics that characterize qualities of flows. In the next section, we discuss objectives and desired outcomes for location-based process design methods, and we then propose several workload leveling metrics.

WORKLOAD LEVELING

OBJECTIVES AND DESIRED OUTCOMES

In lean production, takt plays a key role in synchronizing processes and operations. The workload for a step in a given process may be less than, more than, or equal to the takt imposed by the customer on the process. By matching workloads to the takt, planners can eliminate waste, such as waste stemming from unevenness and overburden (Frigon and Jackson Jr. 2009). In construction, this is done (1) at the strategic level to meet the project deadline and (2) at the operational level to meet phase- or process milestones and objectives such as generating evenness in workflow and avoiding trade stacking.

Workload leveling tries to achieve a steady flow of work for processes, trades, crews, etc. With that said, to define metrics that measure success towards achieving these outcomes, we first define desired outcomes:

O1. Meet customer deadline (phase/process duration) by meeting the customer's takt or by reducing the duration by increasing concurrency.

O2. Achieve constant crew size (Ballard and Tommelein 1999) by reducing the variation of workloads across zones, thus improving trade (location) flow (Sacks 2016).

O3. Increase worker utilization (reduce the time workers wait on work) by providing timely hand-offs of zones and reducing the need for inter-trade coordination.

O4. Increase space utilization (reduce the time work waits on workers) by reducing the variation of workloads across steps in each zone and designing for spatial continuity (Alves and Formoso 2000), thus reducing overproduction waste (Linnik et al. 2013) and improving process (location) flow.

O5. Reduce workload variability by reducing the variation of workloads across steps and zones.

O6. Reduce process step variability by standardizing work and adding a capacity buffer (underloading) to an individual step.

We next identified metrics to measure success in achieving these outcomes.

METRICS FOR WORKLOAD LEVELING

To evaluate and compare the quality of levelness of workloads to meet the desired outcome of a process design, planners need metrics. Different planners may desire different outcomes and thus need different metrics. To accommodate trade-offs and gauge different outcomes, this paper suggests nine metrics, grouped into seven types as Metrics M2 and M4 each have two parts, a and b. These metrics are:

M1. Workload Peak is the maximum workload considering all steps and all zones. The objective is to minimize this peak. This metric is illustrated by the dashed red line vs. the tallest bar in Figure and 2.

M2. Average of Ranges is the average (aka. mean) value of the ranges of workloads, i.e., the difference between the maximum and the minimum workload, but workloads can be grouped in two ways:

M2a. Grouped by Zone: When workloads are grouped by zone, the range of workload is calculated for each zone, and then, the mean of ranges across zones is calculated.

M2b. Grouped by Step: When workloads are grouped by step, the range of workload is calculated for each step, and then, the mean of ranges across steps is calculated.

The objective is to minimize this range. This metric is illustrated by the gap between the solid red line and the solid green line in Figure and 2.

M3. Workload Range is the difference between the maximum and the minimum workloads across all zones and steps. The objective is to minimize this range. This metric is illustrated by the gap between the dashed red line and the dashed green line in Figure and 2.

M4. Range of Averages is the range of the mean workloads per zone or each step. The objective is to minimize this range. This metric is illustrated by the flatness of the purple line in Figure and Figure .

M4a. Grouped by Zone: When workloads are grouped by zone, the mean of the workloads for each zone is calculated and then the range is calculated between means for all the zones.

M4b. Grouped by Step: When workloads are grouped by step, the mean of the workloads for each step is calculated and then the range is calculated between means for all the steps.

M5. Peak to Average Ratio is the ratio of the maximum to the mean of workloads across all zones and steps. The objective is to minimize the ratio between the maximum and the mean of all workloads.

M6. Standard Deviation is the statistical property that measures how dispersed workloads are relative to the mean. The objective is to minimize this standard deviation. A low value means workloads are clustered around the mean. A high value means they are spread out.

M7. Moment is the sum of squares of centroids (= height/2) of all bars in the histogram, i.e., workloads across all zones and steps. The objective is to minimize the moment by reducing workloads or redistributing them.

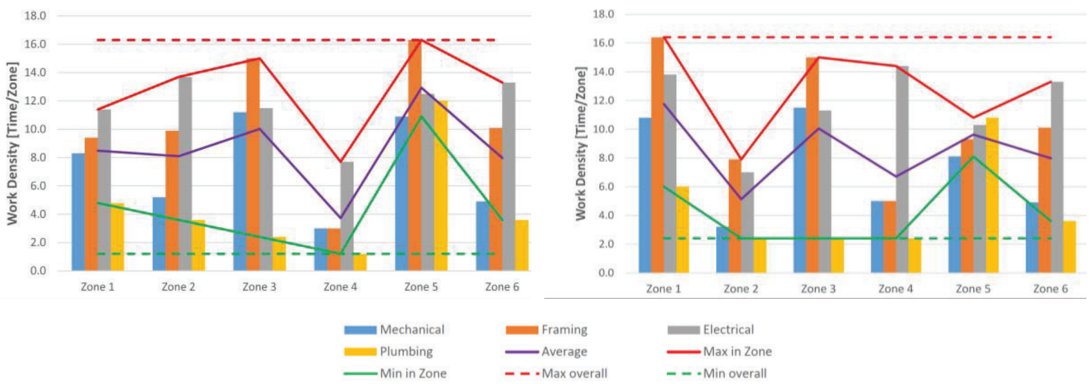

Figure 1: Workload histogram by zone for objective M1 (left) and objective M2b (right)

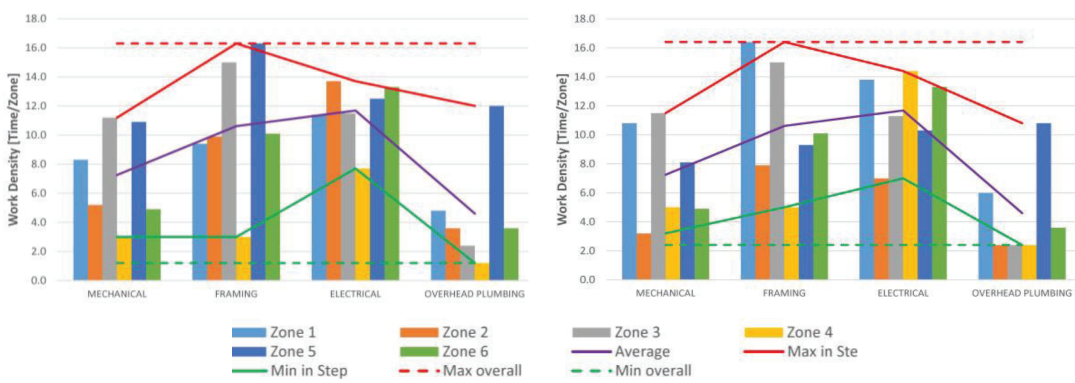

Figure 2: Workload histogram by step for objective M1 (left) and objective M2b (right)

Figures 1 and 2 illustrate the workload histogram after optimization using M1: minimizing workload peak (on the left) and M2b: minimizing the average of ranges grouped by step (on the right), grouped by zone and step respectively. To compare these metrics, we implemented an optimization tool and programmed the metrics as objective functions, as is discussed next.

MODEL IMPLEMENTATION

TOY PROBLEM

Using a GA-based model applied to a toy problem, we programmed the aforementioned metrics one at a time to be the objective function and ran the model to find the optimal solution. The toy problem includes work done by four different trade crews, namely (1) Mechanical, (2) Framing, (3) Electrical, and (4) Plumbing (Figure 3). As these crews are assumed to be working in a linear sequence, each crew's work density map represents a step in the process.

This problem stemmed from a pilot project conducted by Frandson and Tommelein (2014) and Dunnebier et al. (2014) and was also used to illustrate new planning methods including WoLZo developed by Jabbari et al. (2020) and GAWoLZo by Diab and Tommelein (2020).

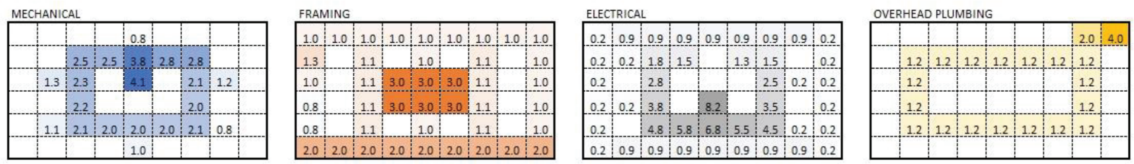

Figure 3: Work density maps for crews in toy problem (part of Fig. 3 in Jabbari et al. 2020)

EXCEL IMPLEMENTATION AND GENETIC ALGORITHM (GA) APPROACH

The toy problem was programmed as a Microsoft Excel based tool, called **XLWoLZo**, which stands for e**X**ce**L** **Wo**rkload **L**eveling and **Zo**ning. The optimization uses the off-the-shelf Microsoft Excel add-in called Solver, provided with the parameters and constraints for work density and zoning as input. The complexity and quality of the problem definition affect the Solver's ability to find a solution. In our case, the problem formulation includes a mixture of continuous decision variables (e.g., the work density in each zone for each step) and integer variables (e.g., zoning grid size). This makes it a mixed integer linear programming (MILP) problem.

In problem formulations where objectives and constraints are non-smooth and non-convex functions of the decision variables, and formulations that use Excel formulas like "IF", both of which are true for this problem, obtaining global optima is unlikely. For such problems, Solver Optimization Methods (2023) recommends using the Evolutionary method, a type of GA. This method provided a solution in a sufficiently short computation time (on the order of several minutes when running Microsoft Excel 365 (v. 1904) on an Intel Core i7-8550U CPU).

The constraints are that zones must be convex, non-overlapping, and non-empty. Recognizing the limitations of Excel to program complex constraints, XLWoLZo constrains zones to rectangles. For example, to divide the work space into six zones, the evolutionary solver first tries to draw a horizontal zone boundary (arrow 1 in Figure 4, where the boundary can be at the bottom of row 1, 2, 3, 4, or 5), thereby dividing the work space in two parts, and then for each part draws two vertical zone boundaries (arrows 2 and 3 at the top in Figure 4, and arrows 4 and 5 at the bottom) resulting in a total of 6 zones.

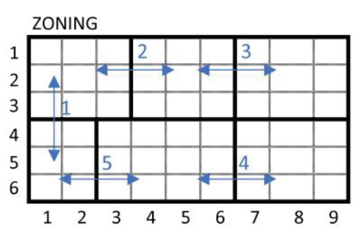

Figure 4: XLWoLZo zone boundary movements

Figure 5: XLWoLZo solution layout for Z = 6 while minimizing workload peak (M1)

The GA moves the zone boundaries until it reaches a solution that it cannot improve upon (based on its convergence parameter or the pre-set computational time limit). Figure 5 shows the zoning solution reached for Z = 6 and the optimization objective set to minimizing the workload peak (M1).

XLWoLZo was run with each of the nine metrics as the optimization objective, one at a time. For each one, the resulting zoning layout and corresponding workload distribution, the values for all 9 metrics were calculated. The results were depicted in workload histograms grouped by zone (e.g., Figure 1) or grouped by step (e.g., Figure 2). Figure 1 shows, when the objective is M1, that the workload for Mechanical trade in Zone 1 is 8.3 time units. This value 8.3 is computed by adding the work density from the Mechanical work density map (Figure 3) for cells that are in Zone 1 (Figure 5). The results from these computations are discussed next.

DISCUSSION

WORKLOAD LEVELING MODEL COMPARISON

The toy problem was solved using WoLZo, GAWoLZo, and XLWoLZo with the number of zones ranging from two to six. In WoLZo and GAWoLZo, the objective was to minimize the workload peak across all the steps in a process according to the WDM (Tommelein 2022). Minimizing the workload peak typically results in minimizing the process duration, barring some exceptions (Jabbari et al. 2020). For XLWoLZo, the model was run 9 times, once for each of the 9 objectives.

As these three models impose different constraints on the geometry of zones, the results they obtain vary in zoning and, correspondingly, application of the metrics gives different results. XLWoLZo has the most restrictive geometrical constraints on zones and therefore produces results that are worse than those of the other two models. The WoLZo Model R divides the work space into rectangular zones, achieving its optimal value of 15.20 time units, which is 7.2% better compared to XLWoLZo's value of 16.30 time units. The WoLZo Model L and GAWoLZo allow non-orthogonal zone shapes and thus result in even better values, respectively 12.30 and 13.50 time units. Admittedly, the geometric constraints imposed by each of these models result in zoning layouts that may not be practical in real-world scenarios. Future research can focus on allowing other zoning geometries and better optimization algorithms.

COMPARISON OF NINE OBJECTIVE FUNCTIONS

Each of the 9 metrics, one at a time, was programmed to be the objective function in XLWoLZo. For each optimal zoning obtained, XLWoLZo also assessed the values of the 8 other metrics. E.g., when optimized for M1 (workload peak), resulting in M1 = 16.30 (Figures 1 and 2), the other metrics have as values M2a = 8.48, M2b = 9.58, M3 = 15.10, M4a = 9.20, M4b = 7.08, M5 = 1.91, M6 = 4.44, and M7 = 1101.88. Conversely, using each of the other 8 metrics as the objective function, resulted in M1's values of 24.30 for M2a, 16.40 for M2b, 16.30 for M3, 22.60 for M4a, 24.10 for M4b, 16.30 for M5, 16.40 for M6, and 16.40 for M7.

Numerically comparing results across all metrics per each objective, the scores for metrics **M2b, M6, and M7** (average of ranges grouped by step, standard deviation, and moment) performed the best in terms of also providing relatively good values for the other metrics. Metrics **M2a, M4a, and M4b** (average of ranges grouped by zone, range of averages grouped by zone, and range of averages grouped by step) performed the worst. Metrics **M1, M3, and M5** (workload peak, workload range, and peak to average ratio) fell in between.

Several metrics are clearly correlated.. M6 and M7 (standard deviation and moment) are both calculated as the product of a constant to the square of each workload and thus their result gives the same results. Standard deviation is not a square but is calculated using variance, which is dependent on the square of workloads.M1 and M5 perform similarly, as mathematically they are the same. Both functions are dependent on the peak, as the average calculated in M5 remains the same for any distribution of workload. This is true in the case of our implementation but can change if a throttle is used to change the underlying work density values (e.g., increasing crew size reduces work density). Strong correlation between metrics show they are interchangeable.

METRICS AND OUTCOME RELATIONSHIPS

In a real-world situation where multiple parties work with conflicting objectives, there is a need to understand the impact of the metrics on different performance outcomes. Balancing between different desired outcomes can be improved by understanding their relationship to the metrics being used to measure them. From the results of XLWoLZo, we observe that:

M1 measures workload peak. Lowering this indicates the possibility of lowering the takt and process duration. Assuming no variation, when M1 <= takt, the process will meet deadline (**O1**).

M2a measures the variation of workload across process steps in each zone. A lower M2a indicates better process (location) flow (**O4**).

M2b measures the variation of workload across zones for each trade or step. A lower M2b indicates better trade (location) flow (**O2, O3**).

M3 measures the variation of workload across all steps and zones. A lower M3 indicates reduced production variability(**O5**). It also improves process (location) and trade (location) flow, but its impact on either is lower than M2a and M2b as it is not biased towards either.

M4a and **M4b** indicates similar effect as M2a and M2b respectively but perform worse.

M5 indicates a very similar effect as M1, and both perform average.

M6 indicates a similar effect as M3 but performs much better due to quadratic versus linear relationships respectively.

M7 indicates a similar effect as M1 but performs much better due to quadratic versus linear relationships respectively. Due to its dependence on the square of workloads, it is reducing higher workloads more than smaller ones.

Takt planners can use capacity buffers to absorb process variability by underloading steps, e.g., to 70-80% of their capacity (Frandson et al. 2015). Thus, sizing of each trade's capacity buffer becomes part of the workload levelling process, as step cycle times need to be lower than the takt. Planners need to balance workers waiting on work (idle time), by providing timely hand-offs of zones, while also underloading to absorb variability. These metrics suggest a distribution of workload values, and with a given target takt, can be used to allocate capacity buffers (**O6**).

Reducing workload variation (by controlling underloading and overburdening) and keeping step cycle time below the takt (with a capacity buffer), results in (1) reduction in work (zones) waiting on workers (steps), in turn improving spatial continuity, and (2) reduction in workers waiting on work, in-turn suggesting timely hand-offs of zones. Achieving both results together is difficult however as one tends to counter the other. This was observed with metrics **M2** and **M4**, both of which are grouped by zone and step. When optimized for grouping by zone, the performance of grouping by steps is poor, and vice-versa.

General contractors (GCs) and trade partners have different priorities as they manage crews between a portfolio of projects. GCs tend to favor process (location) flow, whereas trades favor trade (location) flow, while both manage the related buffers (Frandson et al. 2015). To understand the trade-off between the two desired outcomes we can use a combination of metrics.

Solutions can be employed to deal with these effects, e.g., if a trade is greatly underloaded in specific zones, then the remaining time needs to be planned for the workable backlog, skill development, improvement studies, etc. Another way of understanding the interaction between these two sides involves visually reading the workload histograms. Typically, these histograms are generated with workloads of steps grouped by zones (Figure 1). This makes seeing the variation in workload distribution across steps in a zone easier as opposed to the variation between zones for a step. Thus, to better understand the visual implication of a metric on the workload histogram, we plotted them grouped by zones (Figure 1) and by steps (Figure 2).

To incorporate the trade-offs in real-world scenarios, further study of multi-objective optimization is in order. This may include pareto optimization or creating an aggregate objective function by assigning weights to objectives depending on their relative importance to define an.

We suggest incorporating several metrics on dashboards to support management decisionmaking pertaining to work structuring, zoning, crew sizing, etc.

CONCLUSION

This paper presented an overview of workload leveling for location-based process design using the work density construct, describing various desired outcomes and how they can be measured. Existing models use only the workload peak metric for process optimization. Using metrics described in the literature on resource allocation and leveling in project scheduling as a guide, the paper proposed 9 workload leveling metrics, including workload peak, average of ranges (grouped by zone and step), workload range, range of average (grouped by zone and step), peak to average ratio, standard deviation, and moment.

The identified metrics were programmed for a toy problem on Microsoft Excel (XLWoLZo) as the objective function for a GA to optimize. As expected, the results indicate that there is no single "best" metric for workload leveling. The choice of metric(s) will depend on a multitude of constraints and preferences from the physical site and the project team. Metrics merely provide a quantitative assessment to compare performance toward a desired outcome. Thus, the suggested metrics are later matched with common desired outcomes of location-based process design, and the choice of using a metric is left to the reader. Several objectives (**M1** and **M5**, and **M6** and **M7**) indicate similar outcomes and thus generate similar solutions. These can be used interchangeably and should not be used together when considering different perspectives. Instead, some metrics that indicate opposing outcomes (**M2a** with **M2b**, and **M4a** with **M4b**) should be considered for trade-offs. Overall results and their relationships with desired outcomes showed that metrics **M2b**, **M5**, and **M6**, though meant to measure performance for certain outcomes, can do their work while also balancing other outcomes.

For future research, these objectives can be incorporated into optimization models such as WoLZo or as metrics to support manual workload leveling and zoning using tools such as ViWoLZo. To incorporate the real-world trade-offs, further work may focus on pareto- or other multi-objective optimization, or show metrics on management dashboards for collaborative decisionmaking.

In summary, this paper provides insights into the selection of metrics for workload leveling in planning methods, and it highlights the importance of considering the specific context and objectives of the planning scenario when choosing a metric.

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