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APPLICATION OF THE WORK DENSITY METHOD TO IN-SITU PILE PRODUCTION IN HEAVY CIVIL ENGINEERING

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ABSTRACT

The Work Density Method (WDM) is used in takt planning for defining zones with equal workload. To date, this method has been applied mainly to building construction. This paper investigates the WDM's applicability to equipment-driven processes in heavy civil engineering, specifically to the in-situ production of foundation piles for a highway infrastructure project. Two existing computer-based programs that support the application of the WDM, WoLZo and ViWoLZo, were used to find a suitable grid size based on data from a real-world project. The results show the potential of using the WDM (1) to define zones with equal workloads, given that pile groups are irregularly distributed over the construction site space, (2) to compare different scenarios based on work density as a metric (e.g., scenarios with different uses and sequencing of equipment), and (3) to derive a takt time and process duration when using multiple pieces of equipment that must coordinate their efforts and work in sync. Compared to the building construction application, the heavy civil engineering application reveals new requirements when using the WDM and takt planning in general, regarding the geometrical and logistical needs of equipment-driven operations that constrain how zones can be defined.

KEYWORDS

Production system design, takt planning (TP), Work Density Method (WDM), heavy civil engineering, work structuring, workload leveling, foundation piles, infrastructure project.

INTRODUCTION

As part of heavy civil engineering, in-situ pile production is highly complex due to its variety of variabilities (Fischer et al., 2021). Especially uncertainties related to soil conditions make it hard to plan the piles' production line. The intent of defining a takt plan is to demarcate clear handoffs between predecessor and successor trades, i.e., in-situ pile production followed by the above-ground structure they support, by harnessing variabilities within the production line so that the line's output will reliably meet the customers' target dates (Tommelein, 2020).

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The Work Density Method (WDM) was created to methodically support the use of takt when developing construction process plans (Tommelein, 2017, 2022). The method builds on the concept called work density "defined as the time a trade will require to do their work in a certain area, based on (1) product design, (2) scope of the trade's work, (3) specific steps of the operation in their schedule, (4) means and methods the trade will use, and (5) accounting for crew capabilities and size" (after definition in Tommelein et al. (2022)). While this method was first applied to deliver single- and multi-story buildings, it potentially has broader application across the construction industry. Here, we describe how the WDM can be rethought and adapted to suit the specific requirements of heavy civil engineering projects which, in particular in regard to takt planning, differ in several ways from building projects.

Fundamental distinctions between building construction and heavy civil engineering pertain among other things to the number- and specializations of trades involved, the sharing of resources, and the interdependences among them. In heavy civil engineering, major work requires in-situ production, the simultaneous involvement of specialists, and work space requirements that depend on the equipment being used. On projects with earthmoving processes (Kirchbach et al., 2012), considerable variability will likely be encountered. Such variability and other complexity dimensions of heavy civil engineering projects makes characterizing work densities challenging when creating a takt plan.

Our research objective was to determine whether, despite these differences, the WDM can be applied to the specialized field of in-situ production of foundation piles for bridges in a highway infrastructure project, a type of heavy civil engineering projects. The specific research questions were: (1) how to define the grid cells depending on the space the equipment needs to fulfill the work, (2) how to combine these cells into zones while balancing workloads in order to define a takt for the process involving multiple trades, and (3) how beneficial is the WDM when construction work in distributed irregularly over the construction site space?

To answer these questions, we studied the potential application of the WDM using two different computer-based support tools, namely WoLZo by Jabbari et al. (2020) and ViWoLZo by Singh et al. (2020) and Singh & Tommelein (2023a, b). We assessed the suitability of these tools to model the in-situ pile production process while identifying modeling assumptions made for the implementation of these tools that affect the successful use of the WDM in this context. In general, this paper contributes to knowledge by describing the application of the WDM for takt planning of projects of different types and complexity.

LITERATURE REVIEW

Takt planning has been applied to infrastructure projects (e.g., Fiallo & Howell, 2012, Tommelein & Lerche, 2023), on a variety of phases of building projects such as exterior cladding, interior overhead work, and finishes (e.g., Frandson et al., 2013, Linnik et al., 2013), hospitals and hotels (e.g., Riekki et al., 2023), and other types of projects. These projects are characterized by repetitive work and high fragmentation of the work as they require- and due to the involvement of specialized trades. Coordinating these trades to finish the project within the given time, quality, and budget is challenging.

Takt helps to create concurrency in the schedule, thus resulting in shorter delivery times. Takt planning aims to equalize the time each trade needs to complete their scope of work in each zone to achieve a more-or-less continuous flow of work and trades through space. Trades follow each other sequentially, forming a sequence of process steps called a "Parade of Trades" (Tommelein et al., 1999, Tommelein, 2020) or "train of trades" (a term used in the German-speaking areas). Each wagon in the train represents the scope of work fulfilled within one takt time unit by one (or sometimes several) trade(s). In execution, the takt plan may require the use of adjustment mechanisms (Binninger et al., 2017) also known as "throttles" in production system design, e.g., changes in the number of assigned resources.

Figure 1 illustrates the creation of concurrency using takt planning. The top row shows a process with three trades, one following the other, working in a single zone (Z = 1). Each trade needs a specific time to complete their process step, the so-called workload. The workload depends on the scope, means-and-methods selected, capabilities and quantities of resources, and zoning. The maximum amount of time across all trade steps in the process is called the workload peak. In this example, the workload peak, referred to as T(1), is assumed to be six time units/zone. If one can divide the work space into multiple zones, e.g., into two (Z = 2) or three (Z = 3), and correspondingly divide the step of work done by each trade into smaller steps, then the workload peak T(Z) as well as the duration D of the process can likely be reduced. In theory, increasing the number of zones would mean that the duration can get shorter. In practice, however, there is a limit to how small zones can get and still allow for work to take place. The practical size and shape of a zone will depend on the space each trade needs to effectively complete their step of work within the allotted time.

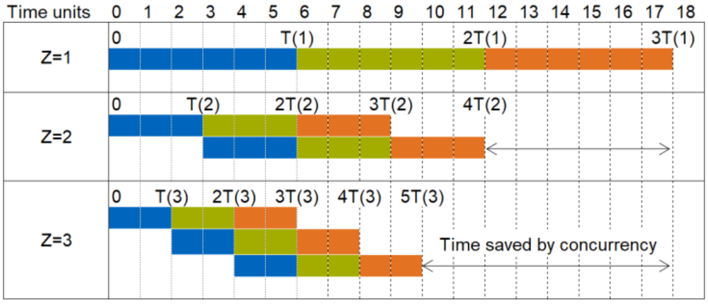

Figure 1: Process with three consecutive process steps, when the work space is divided into one (Z = 1), two (Z = 2), or three (Z = 3) zones to allow for concurrent work (Z: number of zones; T(Z): workload peak) (based on Tommelein (2022))

Formal methods exist to help takt planners with sizing and shaping zones of work. From a workload leveling point of view, data can be used to mathematically determine the work space zoning that minimizes the maximum time any trade in the process needs to complete their work zone by zone. Unlike other space scheduling methods, such as the line-of-balance method, which starts with an *a priori*-defined location breakdown structure, the WDM does not start with *a priori*-defined space units. Instead, it computes each trade's workload in a given zone.

Previous research used the WDM to schedule trades working on interior finishes of building projects. With that type of work in mind, Jabbari et al. (2020) developed a mathematical algorithm, called the Workload Leveling and Zoning (WoLZo) algorithm, to calculate the optimal zoning assuming that the calculated zones would be either rectangular or L-shaped. They defined a zoning to be optimal when it minimizes the workload peak across all steps in all zones. Singh et al. (2020) and Singh & Tommelein (2023a, b) developed a simple visualization of work densities shown in a grid overlaying the work space, programmed in Microsoft Excel. Their Visual Workload Leveling and Zoning (ViWoLZo) program allows users to create zones of any shape. ViWoLZo makes it easy to manually adjust the boundaries of zones, including their size and shape, and compare the workload peak of the process T(Z) to assess whether that process can meet the customers' demand.

METHODOLOGY

APPLIED METHODOLOGY

Since the body of literature relevant to scheduling in-situ pile production processes is limited, we adopted a case-study research methodology. This study was conducted in the context of the master's thesis of Philipp Baumgartner (2023), a co-author of this paper.

To gain fundamental understanding of the study topic, the first and the second authors conducted three semi-structured interviews, 1.5 h each, with four project leaders from three construction companies. These project leaders were considered to be experts in the field, and had been selected on the basis of their local experience and their management position. The interviews centered on understanding the requirements and the details of the Kelly drilling process for pile production in order to document process steps and space needs (Figure 2). The Kelly drilling process is widely used for the production of piles with a large diameter, ranging from 0.6 m to 3 m and up to 125 m deep (Bauer group, 2024). Its flexibility meets various engineering requirements and soil conditions.

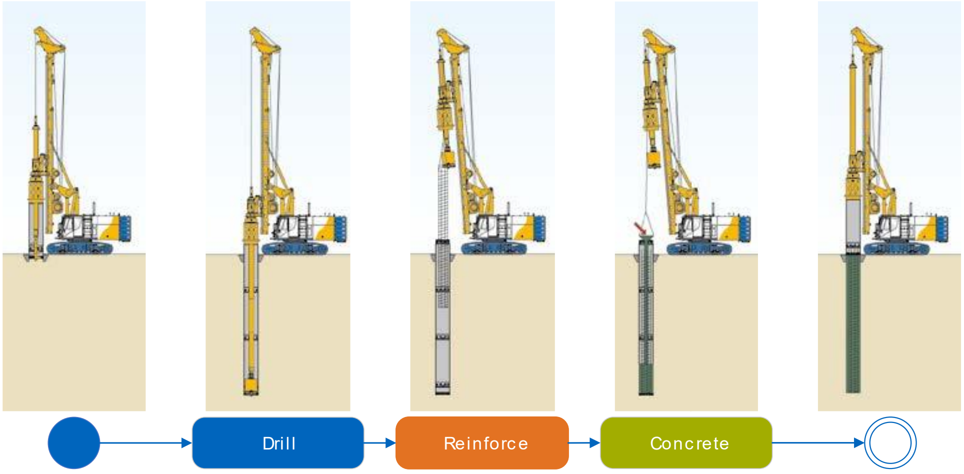

Figure 2: Kelly drilling process: (1) drill, (2) reinforce, (3) concrete (after image from Bauer group (2024))

To assess the feasibility and effectiveness of using the WDM for process planning of heavy civil engineering work, we obtained input data from a real-world highway infrastructure project. Specifically, we focused on the process pertaining to the in-situ production of bridge foundation piles. This project had unique requirements to accommodate challenging soils conditions: single piles had to be produced in a specific order. Detailed records including extensive datasets were available, detailing production times for each process step in every pile. At the time of our study, all piles had already been produced. We thus mapped the as-built construction process using historical data from this project, informed by the interviews we had conducted previously. We used this data later to calculate the work density corresponding to the grid we chose to superimpose over the construction site (work area). The interviews helped with the evaluation of the results.

IN-SITU PILE PRODUCTION

We next describe the pile production system and compare it with the interior finishing phase of building construction (Table 1). As is the case for materials installed as interior finishes in building construction, the product of heavy civil engineering is installed in well-defined locations. In-situ pile production is characterized by the repetitiveness of the process steps to produce the product, but each product can be unique (e.g., in terms of its geometry and material composition). The process resembles linear assembly line production. The pace-setting resource is the Kelly drilling rig. After the drilling rig is positioned, piles are produced in three main steps: (1) drill, (2) reinforce, and (3) concrete (Figure 2).

In contrast, there are differences in the resources. Building construction is typically done by workers organized in trade crews moving flexibly from one work zone to the other, carrying or carting their tools and materials as needed, and relocating relatively small-sized equipment. Heavy civil engineering is dominated by its equipment with an operator and its support crew.

Movement of the drilling rig and its setup takes times and effort. Besides its sluggishness, the drilling rig needs a specific space to work and allow for a safety clearance, and all its auxiliary devices must be kept within reach. Auxiliary devices include temporarily installed casings to stabilize the drilled hole, oscillators to support the drilling and removal of the casings, and tools to drill in different soil conditions. Small front-end loaders or excavators support this heavy equipment by handling its auxiliary devices and material. Even though the equipment is well-instrumented with sensors to assist the operator, (e.g., automated release of a tool), the quality of pile production depends on the operator's and the supporting crew's know-how and skill.

The differences in the resources lead to differences in the type and degree of digitalization used in the process. Whereas building projects may make use of digital standards and Building Information Modeling (BIM), the process of data collection during execution is still highly manual, in part because people mainly do the work. In contrast, the latest civil engineering equipment is instrumented to support with operator-assistance systems and automatically collect large amounts of sensor data during execution for later process analysis (e.g., Fischer et al., 2023). However, the data describing boundary conditions may be uncertain. For example, digital models may not accurately capture the exact depth of soil layer interfaces, boulders, or groundwater levels. Not knowing the soil characteristics makes it hard to automatically select the optimal tool for the equipment or to determine the tool's optimal soil filling level, so that the operator's and support crew's expert knowledge and intervention is still needed (Fischer et al., 2021). Considering the trend of adoption of construction robotics (Brosque et al., 2020) for equipment-intensive processes, our study can inform how the operations are planned of such systems involving human-machine interaction.

Table 1: Comparison of production systems of interior finishing in building construction with pile production in heavy civil engineering

Characteristics	Interior finishing	Pile production
Product	Rooms	Piles
Process	Process steps are performed by many different trades	Process steps are executed mainly by the same trade crew
Resources	Trade crews with tools and relatively-small equipment	Large equipment and auxiliary devices, operators, foreman, 1-2 construction workers
Flow interruptions	Coordination between the trades	High uncertainty due to the soil conditions
Digital technologies in practice	Collaborative planning using BIM; material tracking with barcodes, RFID, cameras, or notification.	Use of GIS (less use of BIM); material tracking with GPS; digital delivery notes; highly automated equipment with operator-assistance systems.

ADAPTION TO THE WORK DENSITY METHOD

To demonstrate the application of the WDM, we adapted Tommelein et al.'s (2022) example to pile production and rethought how one would partition the work space in zones for takt planning. The objective of this rethinking was to find the number and shape of zones that would balance the workloads of steps in the pile production process, and to possibly create concurrency to reduce the process duration. This potential of rezoning to reduce the duration is stated mathematically:

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

where D is the duration of the process, S the number of process steps, Z the number of zones, and T(Z) is the workload peak, defined as the maximum of all trades' workloads in every process step and every zone. The workload is expressed by trade and in time units (e.g., hours) to complete a certain scope of work in a certain zone, so it could be expressed, e.g., or h/m² or h/pile, with the caveat that zones will likely vary in terms of their physical area (Figure 3).

On the theoretical side, Figure 3 depicts the work density maps referring to the production of two single piles (black circles) installed in three consecutive steps, (1) drill (blue), (2) reinforce (green), and (3) concrete (orange). The number in each cell indicates the work density for that cell, and the darker shade of color in a cell indicates a higher work density.

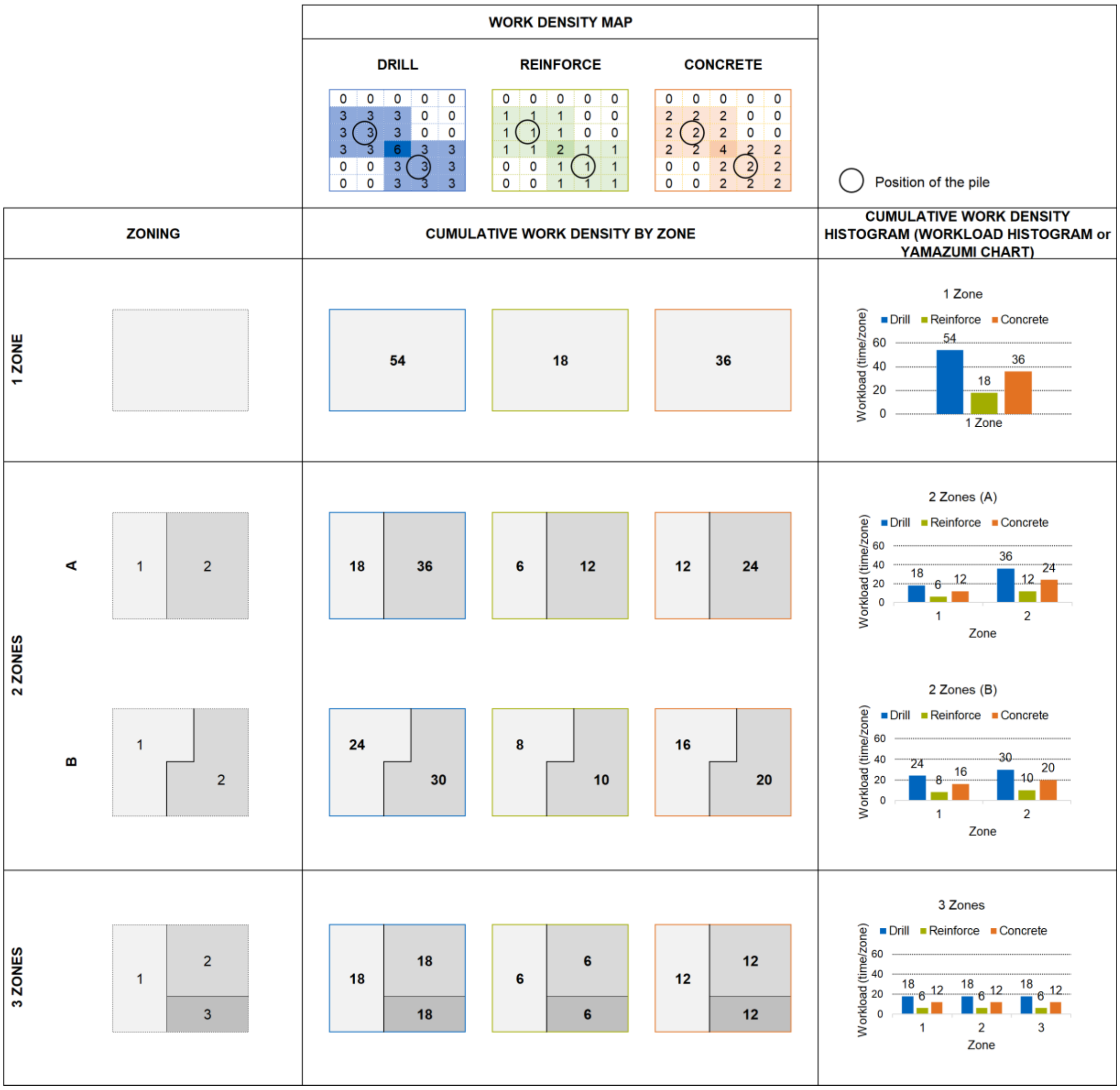

Figure 3: Work density maps and workload histograms for four different zoning alternatives to produce two single piles (after Figure 5 in Tommelein (2022))

For Z = 1, the trade defining the workload peak is the drill trade with T(Z) = 54. In this case, the duration of the process is D = (3 + 1 – 1) × 54 = 162.

For Z = 2, the workload peak may decrease. As the zoning influences the workload, alternative partitions must be considered when trying to even out workloads for any trade, or to reduce the workload peak of the process. The middle of Figure 3 shows partition A with a workload peak of $T(Z_A) = 36$ compared to partition B with $T(Z_B) = 30$.

For Z = 3, the workload peak may decrease further. The bottom of Figure 3 shows one such zoning. In this exceptional circumstance (where the work density maps of drill, reinforce, and concrete are multiples of each other), it is possible to achieve workload evenness within each trade, although there is still unevenness across trades. Evenness across trades can be achieved by combining the reinforce- and concrete trades into a single step.

On the practical side, a certain zoning may be rendered infeasible due to overlapping: if the distance between the piles is too narrow, the space the equipment needs to produce the piles overlap (darkest cells). The space needed depends on the swing radius of the drilling rig (production line) and the auxiliary devices or vehicles (logistics), e.g., casings, tools, a wheel loader for material supply and disposal, or a concrete mixer. Relatively speaking, partition B follows these restrictions best; nevertheless, it is still infeasible due to the overlapping of the zones.

In the case of building construction processes when workload unevenness occurs across trades, it is common to assign more (or fewer) people to trade crews to decrease (or increase) their workload. In the case of the pile production, where the dominance of the drill process step is obvious in all zoning alternatives, the workload per zone cannot be decreased by increasing the number of human resources (but it may be decreased by increasing the skill level of workers, in particular the skill of the equipment operator). One alternative for speeding up the process is to decouple the process steps, so that they are executed by different equipment trades, e.g., (1) drill: for the upper layers of a hole use a drilling rig smaller than the rig needed to drill the deeper layers; (2) reinforce: free up the drilling rig by installing the rebar cage by crane; (3) concrete: pull out casings during concreting by using an oscillator installed in front of a drilling rig.

To sum it up, first, an increase in the number of zones Z can lead to a decrease in the workload peak T(Z) for a certain zoning and, therefore, in the duration D. Second, the workload peak depends on how zones are defined. As mentioned, there is a limitation on any zone's size and shape depending on the space the work practically needs (Jabbari et al., 2020). In the case of pile production, the process is dominated by a highly specialized piece of equipment with a fixed crew. The pile production process duration can be shortened by using multiple pieces of equipment working concurrently in multiple zones.

CASE STUDY

OVERVIEW

The input data are from a completed highway infrastructure project in Rosenheim, Germany. This project involved the construction of a bypass road including two bridges near the German-Austrian border. The project consists of 32 bridge piers, each including any number from 5 to 17 large-diameter bored piles of the same type and ranging from 26 m to 50 m in length. Data from 232 piles in total was used for the case study, including their location on the construction site as well as their production rate. This data was used to test out both computer-based programs, (1) WoLZo and (2) ViWoLZo, made available by the third co-author.

WOLZO

First, we used WoLZo to apply the WDM to the case study. Figure 4 shows the construction site layout overlayed with a grid mesh. We experimented with different grid mesh sized but chose this grid mesh to include multiple piles (independent of their pile groups), allowing the experts enough work space within a grid cell for adjustment during planning and operation.

The production times for all piles within each cell were summed up to create three work density maps, one for each process step. These maps were input to the WoLZo algorithm. The algorithm groups work density grid cells into zones, balancing the cumulative work densities (aka. workload) by zone and by trade to minimize the workload peak of the process and, consequently, determine the achievable takt. The algorithm, constrained to rectangular shapes, achieved optimal results when dividing the area into 14 zones (Figure 5). Figure 6 shows the corresponding workload histogram of the three-step process (S = 3). The workload peak is T(Z) = 41 h and the duration of the process is D = (3 + 14 – 1) × 41 h = 656 h (rounded up to 66 work days of 10 hours/work day).

This first result indicated that: (1) A limit was reached regarding the division of the work space into more zones, as the workload peak was found to correspond to a single grid cell, namely Zone 7 (Figure 5). This high workload is due to the presence of many work-intensive piles in this central location on site. (2) Despite WoLZo's calculation of the optimal zoning, the workloads in the different zones are still uneven. (3) The analysis revealed uneven workloads between process steps across zones.

This unevenness prompted us to combine the reinforce- and concrete step. In theory, the workload is distributed more evenly (Figure 7). In practice this combination is possible, indeed, since the equipment trade of the concrete step uses a drilling rig, and that drilling rig can install the rebar cage. The results show a more even workload histogram across trades (S = 2). The workload peak remains the same, however, the reduced number of process steps results in a reduction of the duration of the process: D = (2 + 14 – 1) × 41 h = 615 h (62 work days).

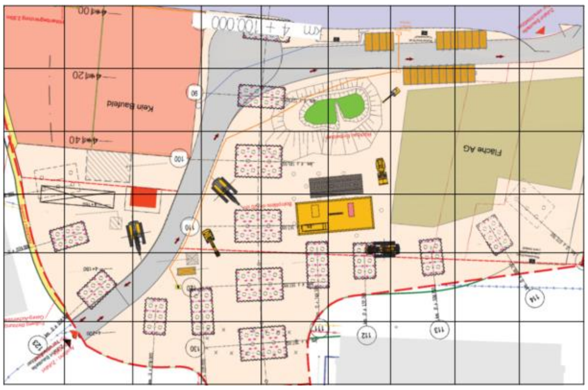

Figure 4: Construction site layout of the case study project overlayed with grid mesh

Figure 5: WoLZo optimal zoning with rectangular shapes for Z = 14

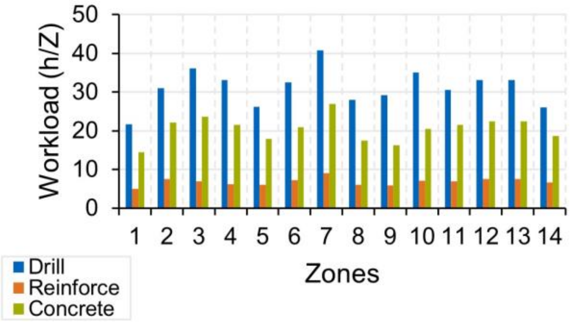

Figure 6: Workload histogram of process steps by zone for three trade steps (S = 3)

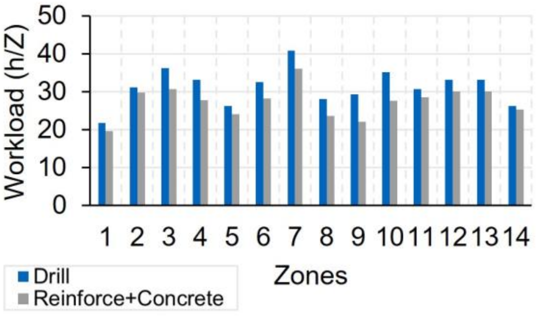

Figure 7: Workload histogram of process steps by zone for two trade steps (reinforce and concrete combined) (S = 2)

ViWoLZo

To further level the workload histogram, the same grid mesh and two work density maps (S = 2) were input to ViWoLZo. Using trial and error, the ViWoLZo user found a better result by going from 14 rectangular zones in the WoLZo calculation to 11 zones (Figure 8). "Better" here means that the distribution of the work densities is more balanced (Figure 10). The new workload peak is T(Z) = 47 h and the duration of the process is D = (2 + 11 – 1) × 47 h = 564 h (57 work days). Compared to the WoLZo results, the process duration is reduced by 51 h which is more than a work week. Despite this improvement, one single grid cell still hasa very high work density (Zone 7). Furthermore, the manually calculated zones are irregular and Zone 5 is split, which may be impractical. Whether to allow zones to be spit, and what shapes zones might take on, are modeling questions (e.g., see Figure 5 in Jabbari et al., 2020).

In pursuit of further improvement, knowing that a finer mesh might enable a zoning with a lower workload peak, the final model focused on the grid mesh size of a cutout of the construction site area, including only four pile groups (frame with dashed lines in Figure 8). Figure 9 shows this cutout with a grid where each cell contains one single pile. It also shows the result of the manual zoning process of this cutout using ViWoLZo, considering the work space needed. The nine zones achieved the most even workload distribution (Figure 11). The workload peak of this cutout is T(Z = 9) = 20 h and the duration D = (2 + 9 – 1) × 20 h = 200 h (20 work days). This final model illustrates the importance of defining a suitable grid mesh and giving careful consideration to process step sizes in order to ensure that zones can accommodate all equipment.

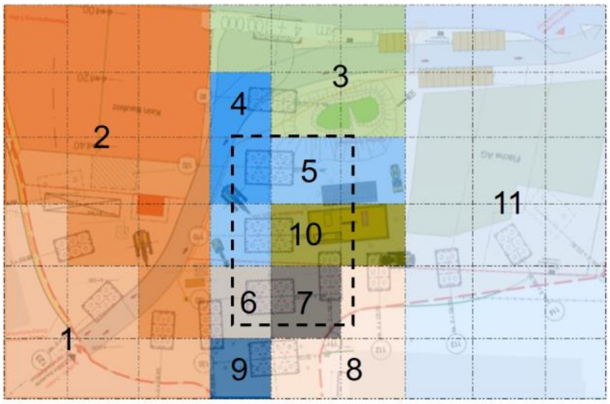

Figure 8: ViWoLZo optimal zoning with manually chosen shapes for Z = 11

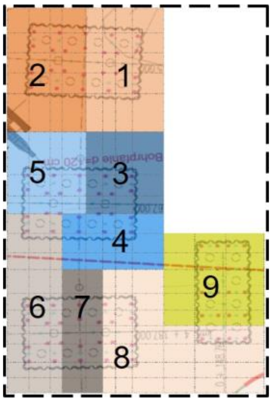

Figure 9: ViWoLZo optimal zoning with one pile per cell for cutout pile groups

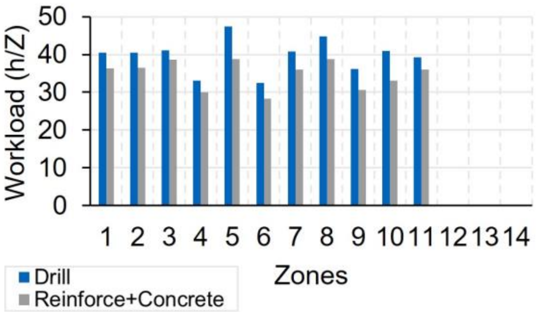

Figure 10: Workload histogram of process steps by zone for two trade steps (reinforce and concrete combined)

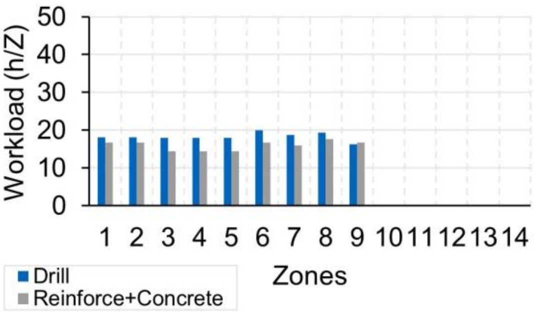

Figure 11: Workload histogram of process steps by zone for selected pile groups (cutout)

RESULTS AND DISCUSSION

The case study showed that the WDM can be applied to in-situ production of foundation piles for a highway infrastructure project, which requires consideration of equipment dependencies. Using a process defined by its steps and the corresponding work density maps as input, two computer-based programs, WoLZo and ViWolZo, were used to zone the work space while achieving a more-or-less even workload distribution for all process steps. Constraints put on the grid mesh regarding work space, the number of process steps, the shape of each zone, and the number of zones all affect the total duration of the process.

The WoLZo algorithm calculated the optimal size and shape of the zones, restricted to rectangular and L-shapes. The resulting zones' workload distributions revealed unevenness, especially per process steps across the zones: the workload for installing the rebar cage (reinforce), and for concreting (concrete) is lower relatively speaking than the workload for drilling the hole (drill). The process steps, reinforce and concrete, were therefore combined in the follow-on study. ViWoLZo gives the flexibility to manually size and shape zones in order to find a more even workload distribution. The zoning obtained show a reduction of the process duration by about 5 work days out of 60, or about 8%.

The study confirmed two notable observations regarding the definition of the mesh size of the grid used in any model. The smaller the grid cells (here one pile in one grid cell), (1) the more flexible the zoning is, and thus the ability to find a lower workload peak (or other process optimum), but (2) the less constrained the zoning is in regard to ensuring that all space requirements are satisfied (e.g., the zone must be accommodate the area of the equipment footprint and requisite surrounding work space).

The case study results reflect the use of a single equipment trade for drilling, reinforcing, and concreting. Further study might consider multiples of that single equipment trade, e.g., using a single equipment trade for a single process step (one for drill, and one for reinforce and concrete), working sequentially from one zone to the next. Decoupling of process steps should allow for a smooth and stable handover from one- to the following step. This further study could be conducted, e.g., through experimental modeling using simulation (Abdelmegid et al., 2022). Practical challenges, such as soil disposal and excavation management, underscore the importance of considering logistics in takt planning. One must balance multiple flows (trades, material supply and removal, equipment, etc.) instead of one flow with a single criterion (here trades) (Tommelein et al., 2022). Besides process requirements, organizational requirements must also be addressed to enable a continuous assembly flow between different trades (Kujansuu et al., 2019). In the presented case study, the zoning was based only on spatial and process constraints. Cost and other resource requirements were not considered.

The case study results significantly underestimated the actual duration of the pile production process, which took 119 work days. Reasons are that the models based on work density did not account for work breaks (e.g., overnight breaks between process steps, with a step ending before the end of a 10 hour work day), nor for the movement and installation of the drilling rig from one pile location to the next. Furthermore, no disturbances or irregularities were considered. However, regularity was embedded in the actual schedule (though it was not takt plan) to facilitate the coordination between specialists, e.g., concrete delivery was scheduled for a specific time each day, even though that resulted in waiting time for the drilling rig.

CONCLUSION AND OUTLOOK

This study's aim was to assess the applicability of the Work Density Method (WDM) in heavy civil engineering projects, demonstrating its requirements within a specific case-study project. Applying a takt planning approach seemed promising for synchronizing the use of resources and process duration planning. The case study showed that takt planning applies to equipment-driven processes. It did so by illustrating the use of the WDM, one method to zone the work space by equalizing workload. Two different computer-based programs, WoLZo and ViWoLZo, were used.

Compared to building construction projects, heavy civil engineering projects have different dimensions of complexity; they can be equipment-driven with a single piece of equipment setting the pace for the overall process. The highly specified equipment trade seems to act like a one-piece workflow, which makes it hard to throttle up and down the pace. This notwithstanding, the case study showed that zoning according to WDM helps even out workloads to reduce the process duration.

Regarding the research questions 1 and 2 on how to define and combine grids and zones, the answer is that equipment space needs as well as logistics must be added as considerations in new models that could build on algorithms such as WoLZo's. In its current implementation, WoLZo constrains zones to be rectangular or L-shaped, and the cells in zones must be contiguous. In contrast, in its current implementation, ViWoLZo allows for flexibility by allowing zones to be split and irregularly shaped (research question 3), but it too needs augmentation to address the aforementioned considerations. Further model extensions could provide support to better represent space needs for equipment, pile groups, etc., and to investigate concurrency by multiple pieces of equipment.

The case study highlighted the need to adapt the WDM to the unique characteristics project types. Further research can look into optimizing crew- and equipment coordination, developing logistics strategies, considering sustainability factors, and integrating the WDM with project management software to enhance project delivery. Validation through benchmarking, education, and training is in order to facilitate the WDM's adoption and success in the heavy civil engineering sector.

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