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QUANTITATIVE INDICATORS IN TAKT PRODUCTION CONTROL: AN EMPIRICAL ANALYSIS

Jaakko Riekki[1], Olli Seppänen[2], Joonas Lehtovaara[3] and Antti Peltokorpi[4]

ABSTRACT

Takt production has improved lead times and stability of lean construction projects. There are several studies about takt planning but research on takt control is scant. Although some quantitative indicators have been proposed for assessing how well sites are able to follow the plan, there are no studies which have used these indicators on real projects on a work package and daily level of detail.

This paper investigates through a case example how previously proposed quantitative indicators of takt control work on a detailed level. We also discuss how the indicators can be interpreted for understanding plan adherence, control actions, and improvement opportunities.

Studying takt control aims to learn why and how production deviates from the plan and how management should act to get the intended production realized. Quantitative analysis with progress data and indicators calculated from them can be used to measure deviation from the plan and the performance of the production system. This paper shows how takt control can be analyzed with flow efficiency and punctuality indicators. Indicators reveal improvement opportunities in outlier trades and takt areas in flow efficiency, the relationship of product and operations flow and go-back work areas.

KEYWORDS

Takt production, production control, quantitative indicators, progress tracking, improvement

INTRODUCTION

Takt production in construction has seen increasing attention from lean construction scholars. So far, the focus of takt production development has been on takt planning, but studies such as Lehtovaara et al. (2021) have qualitatively assessed the effects of takt production in execution. Their results indicated that takt projects tend not to follow the plan exactly but did not elaborate on the nature of issues encountered. Takt control has also been qualitatively touched by Binninger et al. (2017) in the form of proposing a set of possible adjustment mechanisms.

However, studying takt control with quantitative methods could increase understanding on detailed level. The challenge is that quantitative analysis requires gathering data by tracking and recording progress of the schedule on a detailed level. Detailed progress tracking and

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recording can be tedious for the site management team although it can be aided by technology (Keskiniva et al., 2021). Zhao et al. (2021) showed how tracking workers and materials and linking them to schedules can be done with indoor positioning, but this technology is not yet very prevalent.

Despite the challenge, quantitative methods have been used previously for production control in construction in several settings. Hamzeh et al. (2019) proposed a set of metrics and a dashboard aimed at evaluating the performance of the Last Planner® System (LPS) of production planning and control on the team and project levels. These metrics measure the reliability of planning of future work and whether the system is on track towards milestones, but not adherence to a set schedule per se. In location-based management system (LBMS) studies, quantitative methods have been used for assessing production flow. Seppänen (2009) analyzed three LBMS cases quantitatively in detail. Sacks et al. (2017) proposed a quantitative construction flow index (CFI) and tested it in a number of LBMS case projects. For takt production, methods for calculating quantitative flow efficiency measures have been published by Binninger et al. (2019). Binninger (2021) also quantitatively showed the flow properties of an aggregated set of takt cases on a project portfolio level. Further, Alhava et al. (2019) showed with data, how takt production does not always follow the plan but did not analyze the data in detail. Conceptually, Keskiniva et al. (2023) suggested several indicators for takt production performance assessment. However, none of the above-mentioned studies have analyzed takt production quantitatively on a daily and work crew level of detail. This motivates further quantitative analysis in the takt production control context with finer granularity to better understand the actual performance of takt production in execution.

The aim of this paper is to investigate through a case example: (1) How do previously proposed quantitative indicators of takt control work on a daily and work crew level of detail? and (2) How can these indicators be interpreted for understanding plan adherence, control actions and improvement opportunities?

To achieve the aim, a detailed set of progress records of a takt phase of a case project was analyzed. A set of pre-published indicators were used to investigate how they behave with real project data.

METHOD

We first briefly describe the case project and the method of data gathering and extraction, because it has implications on choices that were made for the calculation of the indicators. After that, we introduce the indicators and explain how they were calculated from the data.

CASE PROJECT DESCRIPTION

The case project was a 3-year new construction site that included several phases. One of the phases, the focus of this study, consisted of 178 hotel rooms that were built using takt production. The hotel rooms were small (about 24 m^2) and very repetitive which motivated planning the phase with a two-hour takt time. Each work package, i.e. work done by one trade in a takt area at a takt time, formed their own takt wagon so that the terms work package and wagon are interchangeable, and the term work package is used in this paper. Hotel rooms were done with the takt time of two hours. Production speed was therefore 4 rooms per day since a working day was 8 hours.

The first author participated in the case project in the planning phase and at the beginning of the control phase but was not part of the management team. The first author visited the site and discussed with the management team frequently during the project and occasionally after it had been finished.

SCHEDULE AND PROGRESS DATA

The takt schedule was created in a spreadsheet. The schedule was updated with modifications and progress records by working in one master file. A site manager made the progress record updates daily by marking each work package either started or done. Partial progress rates were not used due to the short takt time. In addition, the site manager modified the plan as required. Copies of the master file were taken daily, and the date was added to the filename. This resulted in a set of 90 schedule version files that represented the current state of plan and progress for each date. Since the progress was recorded daily instead of per takt time, the per takt progress during a day is not distinguishable in the data. This leads to the progress records showing up in batches of four takt times. This has implications for calculating the indicators, which are explained in the following subsection.

The schedule version files were read with a custom program into a custom data structure that contained the progress record for each work package in each takt area at each takt time as well as the planned time of each work package in each takt area at each date. The indicators presented in the following subsection were calculated using custom algorithms that used this data structure. The custom program and algorithms were created by the first author.

INDICATORS

The following indicators were chosen for the analysis: (1) Flow efficiency from product perspective, (2) Flow efficiency from operations perspective and (3) Punctuality. How they are calculated is explained in the subsections below. The flow efficiency (FE) indicators were chosen because they are important measures of value creation and waste and have already been established in previous research by Binninger et al. (2019). Punctuality, as conceptualized by Keskiniva et al. (2023) was chosen because it measures plan adherence, which is also important, but which the FE cannot describe. Other indicators such as continuity, sequence adherence and work in progress are also of interest and require investigation in future studies.

Indicators 1 and 2: Flow efficiency from product and operations perspectives

The general formula for calculating flow efficiency is presented in equation 1. It is the ratio of value-added time to total time such that any non-value-added time between segments of value-added times is added to the divisor (Binninger et al., 2019).

$$FE_i = \frac{t_{i,\text{value added}}}{t_{i,\text{ value added}} + t_{i,\text{ non-value added}}} \tag{1}$$

This can be calculated from two perspectives and separately for planned and actual as presented by Binninger et al. (2019).

The product perspective looks at a single takt area or row in the takt schedule. The times any work package is planned in the takt area are planned value-added times. The times between the value-added times, where there is nothing planned are planned non-value-added times. Takt times before the first or after the last value-added time in the takt area are not considered.

The operations perspective looks at a single work package through takt areas. The times the work package is planned in any takt area are planned value-added times. The times between the value-added times where the work package is not planned in any takt area are planned non-value-added times. Times before the first value added time or after the last value-added time, when all planned takt areas for the work package are finished, are not considered.

The actuals are calculated similarly but instead of looking at the planned times the times recorded with progress are considered.

The flow efficiencies are first calculated for all takt areas and work packages. They can then be averaged over the takt areas for the average product flow efficiency and over the work packages for the average operations flow efficiency. The flow efficiencies can also be calculated in a time series that shows how they change over time. At any given time, the flow efficiency can be calculated as a cumulative value up to a selected time or as a moving average of a chosen time period before the selected time. With a moving average the local behavior of flow efficiency can be understood better compared to the cumulative value.

Also, the total planned flow efficiencies of the schedule can be calculated in a timeseries by considering the active schedule version at each time point. Any changes in the planned flow efficiencies in the timeseries indicate plan changes.

The batch size i.e. how big or small the combination of takt time and takt area is may have a drastic effect on the value of the flow efficiencies, as explained by Binninger (2021). A schedule of the same scope of production planned with a one-day takt time tends to reveal buffers that are implicit in a schedule planned with a one-week takt time. These implicit buffers are calculated as non-value-added time in the flow efficiency equation only for the smaller batch size. For this reason, only schedules with a similar batch size can reasonably be compared directly. In the case of this paper progress was recorded daily instead of per the planned two-hour takt. For the planned flow efficiencies to be comparable with the actual flow efficiencies, the planned flow efficiencies were aggregated to batches of four takt times.

Indicator 3: Punctuality

Based on LBMS delay indicators (Seppänen & Kankainen, 2004) Keskiniva et al. (2023) defined punctuality (P) as the difference between planned and actual work package start (and finish) takt times. The start and end punctualities are calculated by subtracting the ordinal number t_{ordinal} of the planned start or end takt time from the actual start or end takt time for each work package i and takt area j. The general formula is in equation (2).

$$P_{i,j} = t_{\text{ordinal},i,j,\text{actual}} - t_{\text{ordinal},i,j,\text{planned}} \tag{2}$$

This results in two values (the start and the end punctuality) for each work package in each takt area. These can be charted in several ways, for example by showing the punctuality of a work package in each takt area. A negative value indicates delay.

The batch size affects the unit of time that the punctuality is calculated in. For a two-hour takt, the punctuality could be calculated as two-hour units. In the case of this paper the batch sizes of planned and actual do not match and comparing plan with actual with different batch sizes would be misleading. Because of this the planned time of a work package was mapped from the takts to the days that they are in. This leads to a time unit of one day for the indicator.

FINDINGS

A visualization of the schedule and progress record data presented in Figure 1 (interpretation inside the figure) was generated to get a general understanding of how the work progressed. The plan is shown as it was at the end of the phase. There were plan changes during the phase, so the plan would look different depending on the chosen date. The schedule analyzed is also of a limited scope of the phase. Concrete floor drying times caused a delay of several weeks and considerable disturbance for the latter portion of the phase. This was ruled out to not cause unnecessary difficulties for interpretation of the analysis.

Some work packages in front of the train were planned faster than the takt, and some of them were completed faster than planned. This was possible because the limiting factor for starting work was getting water tightness at the top of the building, after which there was plenty of space for the first faster work packages.

It is clear from Figure 1 that the progress tracking breaks down during and after the break planned for two weeks to account for holidays. After the break, there were two large and several smaller batches of tracking data. After those batches, regular updates were resumed. The large batches do not represent reality because they represent several days' worth of progress but are recorded in one day. Due to this, the analysis was done in two parts: (1) a general analysis on the whole schedule with averaged indicators and (2) a more detailed analysis on a segment of the schedule in the beginning of the phase (shown with a dashed line in the bottom left of Figure 1) where production was relatively stable. In the latter we investigate indicators representing individual takt areas and work packages.

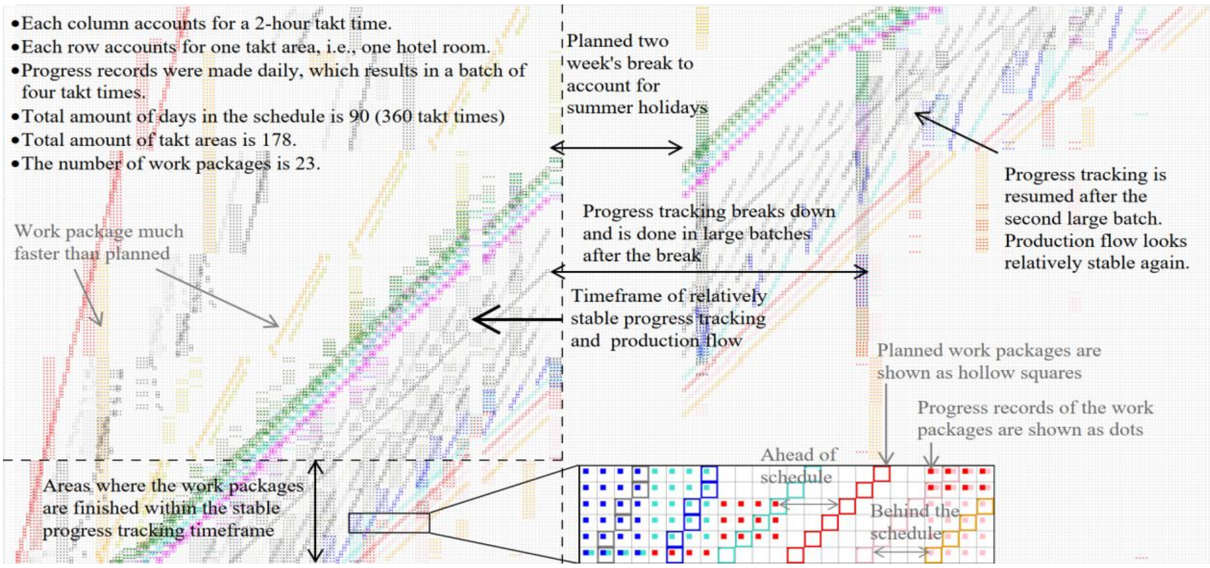

Figure 1: Visualized overview of the schedule and progress record data.

Analysis of the Whole Schedule with Averages

From the schedule visualized in Figure 1, overall flow efficiencies were calculated by averaging over the 178 takt areas for the product perspective and over the 23 work packages for the operations perspective (Figure 2). The planned flow efficiencies represent the average planned flow efficiency of the schedule at the point in time.

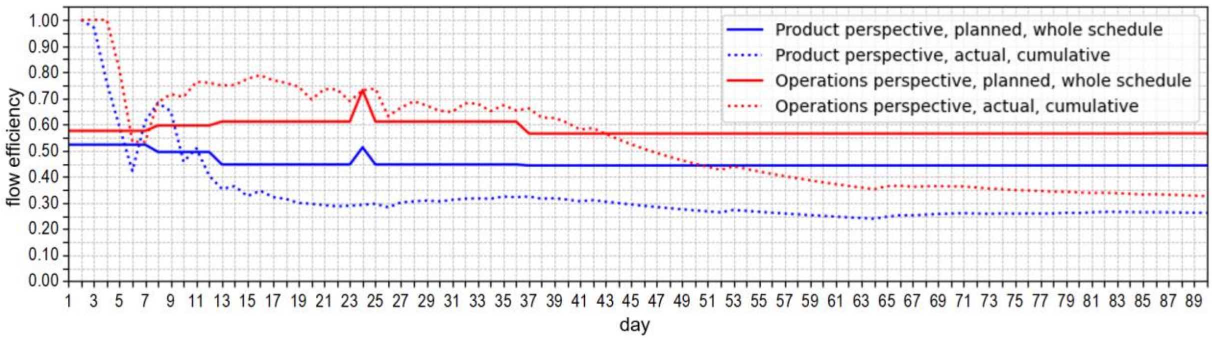

Figure 2: General flow efficiencies averaged over all work packages or takt areas.

The indicators show that plan changes were made at 8, 13, 24, 25 and 37 days. The change at the 24th day seems to have been retracted at the 25th day. In the first plan changes, the operations flow has increased whereas the product flow has decreased. Here some of the faster work packages in front were moved closer together. This decreased the non-value adding times in the operations flow but increased the non-value-adding times in the product flow.

The actuals in the Figure 2 were calculated cumulatively from the start of the work package for the operations flow and from the start of the takt area for the product flow. In the beginning they fluctuate heavily because even one non-value adding time unit will decrease the ratio when the total accumulated time is still short. The further in time the cumulative average is calculated, the more stable it becomes as it approaches the final value at the end of the phase. Both actuals start to decline at about the 42nd day. Here the progress tracking broke down, which caused big gaps in recorded value adding times. The actual indicators lose meaning at that point, but they can show a problem like this. Before breaking down and after the initial fluctuations, the flow efficiencies fluctuate somewhat but stay at a relatively steady level. For product flow the actual is mostly lower than planned, whereas for operations flow the actual stays above the planned before the 42nd day. On average, the work packages have less gaps in their flow relative to what was planned whereas the takt areas were not being worked on as often as was planned.

In the timeframe before day 42, the visualization shows, and site observations confirm, that despite the actual product flow efficiency being below the planned, the phase was mostly able to meet the schedule. Even if there were more gaps than planned in the product flow, the overall flow was good enough. Through the visualization and discussions with the management it was discovered that in some cases one worker had two adjacent work packages and worked on them at double speed but alternating between the two every day. This way they made the same takt but the planned operations flow for both of the work packages was only 50 %, although for the worker the planned flow efficiency was 100 %. This is an effect that was not but should be accounted for when calculating the flow efficiency, and it may be a cause for the higher than planned operations flow efficiency.

The punctuality indicator was calculated by averaging the punctualities of work packages in each takt area. The averaged start and end punctualities of the work packages in the takt areas are presented in Figure 3. The takt areas were worked on in order from left to right. The planned time was aggregated from the two-hour takt to a day.

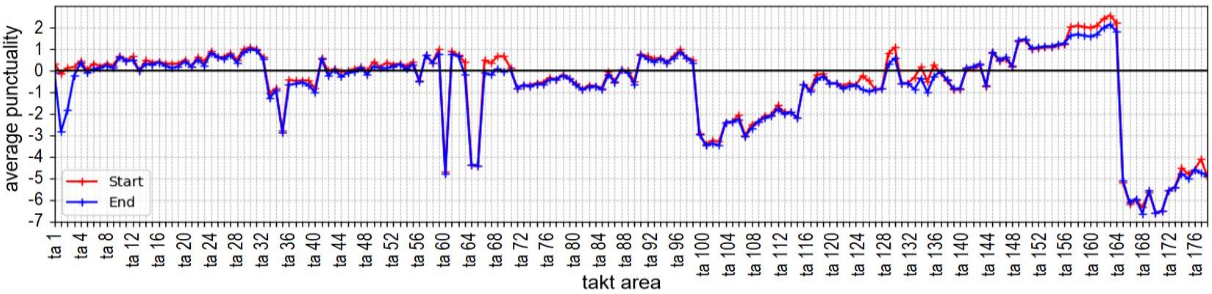

Figure 3: Punctuality at takt areas averaged over all work packages. On the horizontal axis are the takt areas in order from 1 to 178. On the vertical axis is the punctuality in days.

In the second and third takt area from the left, there is a large gap between start and end punctuality. This was due to one work package that was started on time but finished very late because of go-back work in those takt areas. From the third takt area onwards, the punctualities show that the work packages were started and finished ahead of schedule and very close in time to each other. Being ahead of schedule builds up to takt area 33, after which there is a dip to below zero. This is because the last work packages in those takt areas were planned to be finished before the break but were recorded finished in one of the big batches after the break. In takt area 36 that goes deepest below zero, there was a similar kind of go-back work problem as in the second and third takt areas, only this time, the work package was not even started in time. Takt areas 61, 65 and 66 are also outliers of this kind. If outliers are not considered, there is an upward trend in the punctuality after takt area 36, which is expected because the big batch of records is getting nearer in time in each subsequent takt area. In the middle segment of the graph there is more erratic behavior that can be traced to the progress record batches but are not studied here in detail. After the clearest example of batch recording at takt area 100, there is again an expected upward trend. The big dip at takt area 165 on the other hand corresponds to the start of the last floor of the building where the layout was different from the previous ones. Site observations confirm that the production flow was affected by this. The punctualities show that production falls quickly several days behind schedule, but that progress continued after that. Disregarding the progress record gaps, the punctuality clearly indicates whether production is ahead or behind the schedule.

ANALYSIS IN MORE DETAIL DURING THE STABLE TIMEFRAME

More detailed analysis is limited to the takt areas that are finished within the stable timeframe. For the operations flow, the focus limits only to the timeframe. The number of days in the analysis is 41, the number of takt areas is 33 and the number of work packages is 23.

Product flow of takt areas is presented in Figure 4. The cumulative values fluctuate in the beginning and gain stability as they approach the final value at the end. Fewer disturbances are shown by the cumulative indicator at the end of the time series. In contrast, the moving average shows how the flow efficiency behaves locally.

The graphs in Figure 4 show that in general the actual flow efficiencies of the takt areas are at a lower level than planned. The actuals also continue further in time than planned because they were finished later than planned. By visual inspection, there also seems to be more variation in the flow efficiencies both in the cumulative and the moving average. The indicator also shows that the actual flow efficiencies seem to get lower towards the end of the phase. Based on discussions with the site management team, this may be due to the last work packages in the work queue having a lower work content compared to their predecessors. To optimize operations flow, the crews wait for several takt areas to be available so that they can finish them in a bigger batch. This also explains why some of the takt areas are finished later than planned.

The large spread in the first half of the planned moving average is explained by the early faster work packages that create a gap of non-value adding time before the next work packages. This gap is small for the first takt areas but gets larger for the subsequent takt areas. Moving average eliminates this effect after day 20.

Holidays, especially when close to the beginning of a work package, cause a disturbance in the cumulative flow efficiency. Holidays were planned breaks, but work was allowed as extra buffer and therefore they were not removed from the schedule and analysis. Plan changes also cause difficulty for interpretation, especially if they happen retroactively.

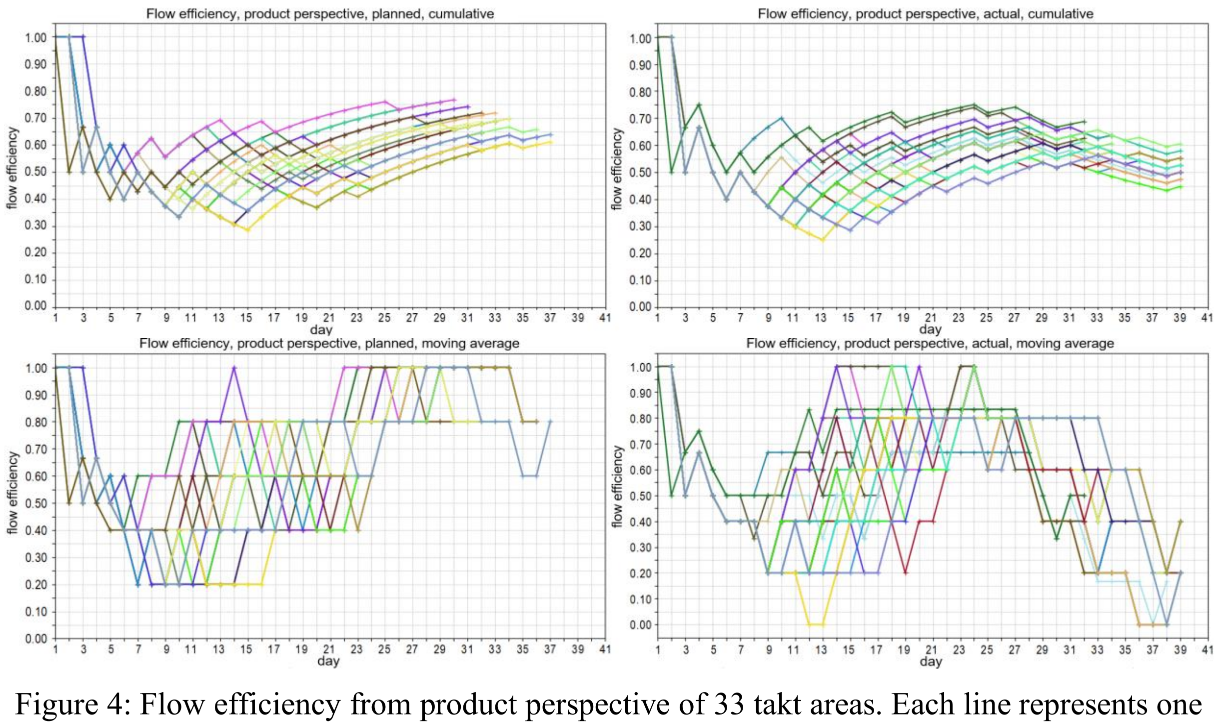

Figure 4: Flow efficiency from product perspective of 33 takt areas. Each line represents one takt area. Top left planned is cumulative, top right is actual cumulative, bottom left planned moving average, bottom right actual moving average.

An example of operations flow of work packages is presented in Figure 5. By visual inspection, the variation in the actual flow efficiencies of different work packages is bigger than planned. Some of the work packages have lower than planned actual flow efficiency, but others have a higher than planned actual flow efficiency. As the averaged analysis suggested, the actual operations flow seems to be on a higher level than planned for most of the work packages, which could be caused by two work packages assigned to one worker. Others however had more gaps than planned, which could be due to them having waited for a batch of takt areas before coming to finish them in one go. The root causes for this kind of variation should be investigated to better understand how to balance the schedule.

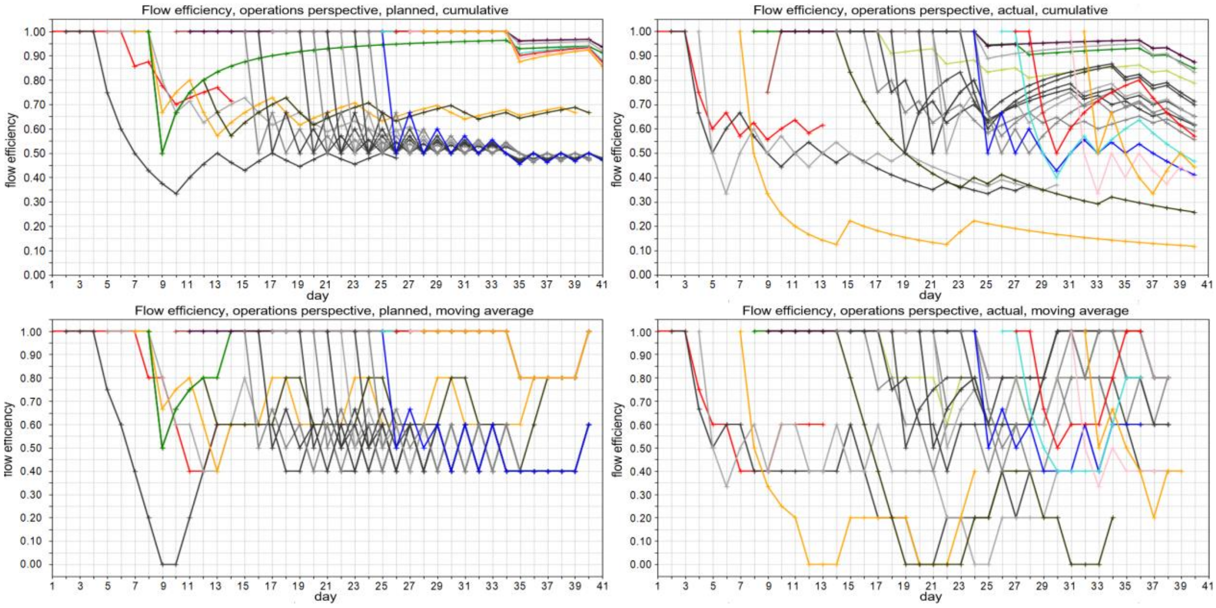

Figure 5: Flow efficiency from operations perspective of 23 work packages. Each line represents one work package. Top left is planned cumulative, top right is actual cumulative, bottom left is planned moving average, bottom right is actual moving average.

The start and end punctualities of the work packages in the 33 takt areas are presented in Figure 6. For the most part, the start and end are close to each other, which means that work was finished quickly after starting. The punctualities fluctuate around zero but seem to be more ahead than behind. This suggests that production was mostly able to keep to the schedule even though it was not followed rigorously. In the end punctuality, the outlier that falls out of the figure caused the drop in the averaged case. The yellow line with chronically low punctuality is the last work package (closing the lowered ceiling drop) in the phase considered. By investigating the individual work packages the causes for effects in the averaged analysis can be narrowed down. The single outlier point in takt area 14 is due to a work package that was not planned in its adjacent takt areas.

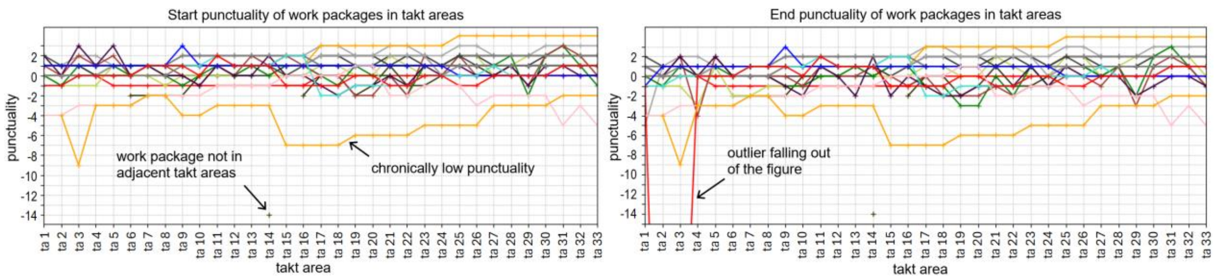

Figure 6: Start and end punctualities of each of the 23 work packages. Each line represents one work package. On the left is the start punctuality, on the right is the end punctuality.

Figure 7 shows how the flow efficiencies behave when looking at individual takt areas. Takt areas to look into were chosen from the punctuality graphs in Figure 6. Takt area 2 was outlier related to end punctuality, but its effect is not visible in the flow efficiency of the same takt area. On the other hand, takt area 8 seemed like one of the least problematic from the point of view of punctuality, but it shows more fluctuation in flow efficiency compared to the takt area 2. This tells us that the indicators do not predict the behavior of the other and indicate different qualities of the production system. In both takt areas, the actual product flow is again mostly lower in efficiency than planned. But it can be noted that there are also periods where the actual flow efficiency is higher than planned. This indicates that the time periods where production is not planned are still used to do work in the takt area. The effect of having a lower flow efficiency at the end is visible here also.

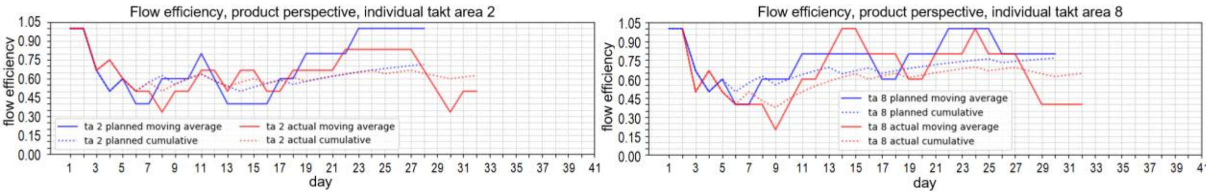

Figure 7: Flow efficiency from product perspective of two individual takt areas. Takt area 2 on the left and takt area 8 on the right.

Figure 8 shows in more detail the flow efficiency of individual work packages. These were chosen to investigate what the difference between two adjacent work packages may look like. The work package 8 was before the work package 9.A in the work queue. Work package 8 has very stable and high flow efficiency with only one interruption on day 25. This does not, however, indicate that the work package necessarily worked the takt areas in the order that was planned, only that the work crew worked somewhere at almost every takt time. Since the product flows were, in general, lower than planned, it is highly probable that this work package took advantage of any free takt areas to prevent interruptions. This could be taken as evidence of adjustment mechanisms being used. Although 9.A has lower flow efficiency, here it is seen for a single work package, how the actual operations flow is higher than planned. This seems like an example of a work package that was planned every other day. The visualization confirms this and that it was planned at double speed to keep following the takt. Through discussions with the management team, it was found out that the worker assigned to this work package was indeed assigned to the adjacent similar work package to work on in the in-between days. The operations flow efficiency indicator as it was calculated here for a work package of this kind is therefore misleading and should be modified to account for the workers used.

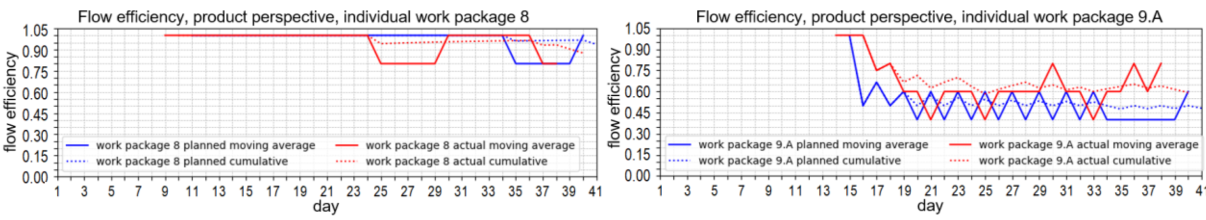

Figure 8: Flow efficiency from operations perspective of two individual work packages. Work package 8 on the left and work package 9.A on the right.

DISCUSSION

The punctuality shows that the schedule was mostly met even with lower than planned product flow. That takt production can provide sound production control even if the plan is not followed exactly has been found in previous qualitative studies such as in (Lehtovaara et al., 2021). The higher than planned operations flow efficiency could be caused by workers alternating between two double speed work packages but also by its prioritization over the product flow as suggested by Binninger et al. (2019). The calculation method could be modified so that it considers the flow efficiency of workers instead of work packages.

Seppänen and Kankainen (2004) found in LBMS studies that discontinuities were the main disturbance that caused late finishes although tasks were started early. They also found that time buffers decrease interruptions. Here in contrast time buffers were minimal but tasks were mostly finished close to starting, which suggests few disturbances. Also, strong signals of cascading delays as described by Seppänen (2009) in LBMS case studies were not found. This supports the interpretation that time buffers recommended by LBMS are not essential to avoid trade collisions and production slowdowns in takt production.

It must be noted that the study focused on a limited single phase in a single 2-hour takt time case. The limitation was intentional to be able to focus on investigating the indicators. Had the whole scope of the phase or the project been considered, the results would have been more difficult to interpret. Therefore, although the discussion above does indicate the applicability of the indicators for studying takt control, it does not, however, allow for generalization.

Other indicators such as continuity used by Seppänen and Kankainen (2004) in LBMS studies or the proportion of work performed out of sequence parameter of the CFI (Sacks et al., 2017) could also be adapted to takt production. In addition to the punctuality, Keskiniva et al. (2023) conceptualized six more indicators to evaluate takt production performance. These could be further investigated to find out their value and applicability.

Also, as Binninger (2021) pointed out, the connection between different levels of planning and control (so called macro, norm and micro levels) have different perspectives. A 2-hour takt time is very close to the micro level and the way the indicators translate to the norm and macro levels should be investigated. One issue of this sort was run into in the discussion above about whether to track a worker or a work package. Further, affirming the findings of Binninger (2021), this study also indicates that there is much room for improvement through improved control practices and methods.

CONCLUSIONS

Returning to the research questions, it was shown in this paper that with progress record data, quantitative indicators such as flow efficiency and punctuality can be used to understand the nature of production on a daily and work crew level of detail. The indicators can show how the production system works overall and trace deviances to individual work packages or takt areas. For example, outliers and peculiarities can lead to relevant conclusions about takt control. They can also reveal plan changes and variabilities involved in production flow. There is plenty of opportunity for more research with more case projects in different settings and with a wider range of indicators. For example, understanding better the question of flow perspective prioritization and how and why takt production reduces the disturbances expected by LBMS could be some of the goals. Also, with such a short takt time as two hours the indicators relate to individual workers but with longer takt times such as one week the interpretation will probably be different. Expanding to other settings such as these warrants for future research.

In future research, setting up a link between the production control indicators and project delivery outcomes could be valuable. Companies should be able to set quantitative project level objectives and use the indicators to assess and direct improvement towards them across projects. This could also reveal common pain points to focus management attention.

Also, forecasts of the indicators could be developed to highlight the impact of problems, to set policies and to help commit to control actions. Dashboards of real-time indicators could allow site management to get focused information of deviations.

REFERENCES

Alhava, O., Rinne, V., Laine, E., & Koskela, L. (2019). Can a Takt Plan Ever Survive Beyond the First Contact With the Trades On-Site? *Proceedings of the 27th Annual Conference of the International Group for Lean Construction (IGLC), Dublin, Ireland.* (pp. 453-464) https://doi.org/10.24928/2019/0261

Binninger, M. (2021). *Untersuchungen zum Arbeitsfluss in getakteten Bauproduktionssystemen aus Perspektive von Generalunternehmern* (Publication Number 75) [Doctoral dissertation, Karlsruher Institut für Technologie]. https://doi.org/10.5445/KSP/1000139278

Binninger, M., Dlouhy, J., & Haghsheno, S. (2019). Flow in Takted Projects – A Practical Analysis of Flow and Resource Efficiency. *Proceedings of the 27th Annual Conference of the International Group for Lean Construction (IGLC), Dublin, Ireland.* (pp. 1271-1282) https://doi.org/10.24928/2019/0228

Binninger, M., Dlouhy, J., Steuer, D., & Haghsheno, S. (2017). Adjustment Mechanisms for Demand Oriented Optimisation in Takt Planning and Takt Control. *Proceedings of the 25th Annual Conference of the International Group for Lean Construction (IGLC), Heraklion, Greece.* (pp. 613-620) https://doi.org/10.24928/2017/0086

Hamzeh, F. R., El Samad, G., & Emdanat, S. (2019). Advanced Metrics for Construction Planning. *Journal of Construction Engineering and Management*, *145*(11). https://doi.org/10.1061/(asce)co.1943-7862.0001702

Keskiniva, K., Saari, A., & Junnonen, J.-M. (2021). Takt Production Monitoring and Control in Apartment Renovation Projects. *Buildings*, *11*(3). https://doi.org/10.3390/buildings11030092

Keskiniva, K., Saari, A., & Junnonen, J.-M. (2023). Indicators for Takt Production Performance Assessment—A Conceptual Study. *Buildings*, *14*(1). https://doi.org/10.3390/buildings14010050

Lehtovaara, J., Seppänen, O., Peltokorpi, A., Kujansuu, P., & Grönvall, M. (2021). How takt production contributes to construction production flow a theoretical model. *Construction management and economics*, *39*(1), 73-95. https://doi.org/10.1080/01446193.2020.1824295

Sacks, R., Seppänen, O., Priven, V., & Savosnick, J. (2017). Construction flow index: a metric of production flow quality in construction. *Construction management and economics*, *35*(1-2), 45-63. https://doi.org/10.1080/01446193.2016.1274417

Seppänen, O. (2009). *Empirical research on the success of production control in building construction projects* [Doctoral dissertation, Helsinki University of Technology]. http://lib.tkk.fi/Diss/2009/isbn9789522480613/

Seppänen, O., & Kankainen, J. (2004). Empirical Research on Deviations in Production and Current State of Project Control. *Proceedings of the 12th Annual Conference of the International Group for Lean Construction (IGLC), Helsingør, Denmark.*

Zhao, J., Zheng, Y., Seppänen, O., Tetik, M., & Peltokorpi, A. (2021). Using Real-Time Tracking of Materials and Labor for Kit-Based Logistics Management in Construction. *Frontiers in Built Environment*, *7*. https://doi.org/10.3389/fbuil.2021.713976