

# Singularity Functions for Early Warning Guidance in The Last Planner System®

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## Abstract

**Question:** Q1: How to enhance the control aspect of LPS be enhanced before during the execution week? Q2: Can a metric be developed to quantify the ability and reliability of crews to implement required within-the-week improvements to their production rates?

**Purpose:** To improve the execution of Weekly Work Planning by monitoring project progress on a daily basis to have enough time for corrective measures, catch up to the planned schedule, and minimize waste in time and resources.

**Research Method:** Design Science Research (DSR) is the research methodology for this study, where a numerical example demonstrates the functionality of the developed tool over different scenarios.

**Findings:** The research offers a user-friendly tool that fits within existing LPS philosophy and whose graphical output is simple enough for most site personnel to understand. A new metric that quantifies the ability of crews to implement improvements in their production rates is developed.

**Limitations:** The new approach should be tested on construction projects to prove its efficacy. Further development could transform the proposed computer tool into an interactive mobile application of lean concepts to support process monitoring and controlling.

**Implications:** The Proposed tool and metrics can aid planners in managing production and introduce within-the-week adjustments to reduce the impact of variability.

**Value for practitioners:** The research offers a practical tool to aid the control aspect within the LPS for CPM, TTP, and LBS schedules. Moreover, it aims to provide a proactive approach in control, where LPS metrics are predicted based on execution progress.

**Keywords:** Singularity functions; Last Planner System (LPS); Lean Construction; Percent Plan

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Complete (PPC); Process Reliability Index (PRI); Weekly Work Plan (WWP)

**Paper type:** Main paper

## Introduction

The goal of Lean Construction is minimizing waste and optimizing value and performance (Nguyen and Waikar 2018). According to LPS, a lean production management system, project control should be based on a proactive approach that allows corrective and preventive measures in addition to early identification and minimization of deviations (Hamzeh, Ballard, and Tommelein 2012). Several metrics are being used under the Last Planner System to track project performance, including Percent Plan Complete (PPC) and Process Reliability Index (PRI). The PPC tracks reliable promising at the WWP level, which is the most detailed phase of LPS (Hamzeh, Ballard, and Tommelein 2012). It is calculated at the end of the execution week by measuring the percentage of tasks completed relative to those planned (Hamzeh, Ballard, and Tommelein 2008). The PRI is a planning index of the reliability of the value of the production rates that are given by crews. It compares the actual activity progress to the planned progress (Gonzalez, Alarcón, and Mundaca 2008). It is measured at the activity level and has been found to function better at quantifying the said reliability than PPC (El Samad, Hamzeh, and Emdanat 2017).

Location-Based Scheduling (LBS) is a relatively new scheduling method (Seppänen 2013). In LBS, the sequence of process control goes as follows: Monitoring progress, forecasting, then identifying and collaboratively solving problems. Another scheduling technique is Takt Time Planning (TTP), which dictates different working areas to have different production rates. All locations or working areas are executed in the same duration and in the same pace, which is Takt time. Takt time scheduling helps ensure standardized schedules by preventing variations in production rates.

Deficiencies exist in practice, because current metrics are a ‘thermostat’ approach to problem solving (Liker 2004) that means corrective measures are reactive. Merely detecting a problem after it has already occurred does not facilitate improving the performance. According to lean principles, an alert is issued once a defect (Liker 2004) (or deviation in construction terms) is detected to triggers proactive measures before the problem grows. Another gap exists in the usage of PRI, which is not linked to the ability of the current number of workers who finish the required work. Moreover, LBS tools are limited to locations. No comprehensible approach exists that combines all scheduling techniques such as Critical Path Method (CPM), TTP, and LBS. Finally, no metric has yet been developed that can reflect the reliability and ability of the project team members to apply the required improvements on a weekly level.

Improving the reliability of WWP (i.e. increasing PPC) will improve overall schedule performance (Hamzeh, Ballard, and Tommelein 2012). Moreover, PPC is negatively correlated with cost deviation, thus higher PPC means lower cost deviation (Formoso and Moura 2009). To improve project performance, PPC is forecasted before the end of each execution week. This way, project participants can detect deviations from the planned schedule, which is linked to

TTP, and implement corrective actions to compensate for expected delays. This paper also links PRI to the capacity of the current crews. Lastly, a new metric is presented to give the team the ability to make improvements and actually finish activities on time. It aids the principle of Kaizen or continuous improvement, a pillar of the lean philosophy.

This paper is inspired by the lean thinking and makes several additions to LPS. It aims to enhance project monitoring and control at the level of the WWP by combining proactivity with continuous improvement by early detection of deviation to increase the performance by the end of the execution week. Its mathematical model employs singularity functions and implemented in a computer tool. Input cells collect data from linear schedules to automatically calculate outputs for the forecasted PPC, required improvement in production rates, resource allocation and congestion, and the risk of occurrence of cascading delays. Metrics for improvement are developed.

## Literature review

To identify and minimize deviations between planned and actual progress, a need exists for an accurate tool to monitor activity performance. Singularity functions offer a mathematical solution. The functions are mathematical known for their mathematical operator (bracket), and they were previously used for analyzing physical loads on structural beams. Their newer application in construction management is described in the following section.

## Singularity functions

Singularity functions offer a flexible and continuous description of discontinuous phenomena (Lucko 2007). They can model projects with horizontal (e.g. roads, tunnels, pipelines) or vertical (e.g. high rises, towers) geometry, and longitudinal spatial or repetitive nature (Lucko 2007). Previously, structural engineers applied them to derive the shear and moments along beams under different loads (Beer et al. 2014). Their basic term is defined in Equation 1.

$$\langle x-a \rangle^n = \begin{cases} 0 & \text{for } x < a \\ (x-a)^n & \text{for } x \geq a \end{cases} \quad (1)$$

Where  $x$  is the variable under consideration,  $a$  is the lower boundary of the current segment, and  $n$  is the order of the phenomenon that changes at the start of the segment. If  $n$  is zero, the term is a step function, but if it is one, it is a linearly growing slope, and so forth. Table 1 lists various papers on their applications for the construction industry.

Singularity functions have advantages: Their expressions can be visualized in graphs to facilitate understanding by site personnel. Their terms includes parameters for activity start times and productivity rates (Lucko 2009) to calculate finishes. They can be added or subtracted to represent varied behavior of activities over time (Lucko 2007).

Despite the various papers that have been published thus far on their usage in construction management, no research has yet been done to integrate singularity functions with project control in lean construction within the LPS.

**Table 1 Papers on Singularity Functions: Titles and Usages**

Title	Usage
Computational Analysis of Linear and Repetitive Construction Project Schedules with Singularity Functions (Lucko 2007)	Construction projects characterized by their longitudinal spatial or repetitive nature, e.g. high-rise buildings, highways, utility pipes
Productivity Scheduling Method: Linear Schedule Analysis with Singularity Functions (Lucko 2009)	Projects with horizontal (highways, tunnels, pipelines) or vertical (high rises and towers) linear geometry, or with repetitive operations. Time and amount buffers generate a critical path.
Modeling Resource Profiles with Singularity Functions (Lucko 2010)	Optimum (i.e. levelled) resources (mostly labor or equipment)
Modeling Cash Flow Profiles with Singularity Functions (Lucko and Cooper, III 2010)	Detailed analysis of cash flows in projects
Spatially-Constrained Scheduling with Multi-Directional Singularity Functions (Lucko, Said, and Bouferguene 2014)	Most projects, because they all depend on the available workspace within a physical location. Starts by activity ordering, stacking, then finally spatial conflict resolution, considering possible time gains
A Unified Quantitative Model for Project Management with Singularity Functions (Su and Lucko 2016)	Projects that are geometrically linear or repetitive in operations. Unifies schedules, cash flow, and resources and transforms them from 2D into 3D
Work-Path Modeling and Spatial Scheduling with Singularity Functions (Isaac et al. 2017)	Minimizing project duration and spaces occupied by crews

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## Last Planner System®

A primary principle of the construction management process is planning and control (Alarcón and Calderón 2003). LPS aids in enhancing project performance and planning reliability. It is used by contractors to enhance on-site workforce productivity and also allows for improvements in both safety and quality (Oakland and Marosszeky 2017). LPS acknowledges fundamental shortcomings of forecasts: The more detailed they are, the more inaccurate they may be, and the farther they look into the future, the more uncertain they become (Nahmias and Cheng 2009).

The LPS divides project planning into four steps: First is Master Scheduling (Should) to find the planned project duration via CPM calculations and set milestones. Second is Phase

Scheduling (Can), where gross constraints are identified, and reverse phase scheduling is performed. Phase scheduling links work structuring with production control (Ballard and Howell 2003). Third is Look-Ahead Planning (Will) that is spread over 2-6 weeks while tasks are broken down and made ready. Fourth is the WWP (Did), where reliable promising is practiced, PPC is measured, and reasons of plan failure are acted upon (Hamzeh, Ballard, and Tommelein 2009; El Samad, Hamzeh, and Emdanat 2017). The WWP, which has the most schedule detail, should contain sound assignments that are made ready by removing any constraints that prevent execution. At this stage, learning from plan failures takes place to prevent their emergence in the future.

Metrics proposed by LPS aim to assess project performance by measuring anticipated tasks (TA) and tasks that are made ready (TMR). PPC is the percentage of completed tasks of those planned (Hamzeh, Ballard, and Tommelein 2012):  $PPC = \text{Did}/\text{Will}$  (El Samad, Hamzeh, and Emdanat 2017). PPC shows production planning efficiency and workflow reliability (Chitla and Abdelhamid 2003). It indicates the reliability of the promises made, and relates to labor productivity (Hamzeh, Ballard, and Tommelein 2012). PPC is calculated at the end of the week of execution. Another metric is PRI, which is positively correlated to activity performance (Gonzalez, Alarcón, and Mundaca 2008). It is the ratio of actual weekly activity progress to that forecasted:  $PRI = \text{Actual Production Rate} / \text{Forecasted Production Rate}$ . Since it compares actual to planned progress, an issue might arise if the plan was not optimal. Planners should therefore set a baseline that is near optimal for PRI to be relevant.

(Abou-Ibrahim et al. 2019) recently addressed the effects of capacity planning on project performance. They found that two barriers hamper the planners' ability to accord between a crew's workload and capacity in the WWP during look-ahead planning: (1) The planners' inability to predict the workload that can be handled by the crew; and (2) the difficulty of specifying what activities will be unconstrained and ready for execution beforehand (ibid.). Load is defined as the amount of work that needs to be done in a predefined set of time; capacity is the amount of work that crews can execute. They described two types of planners - informed planners, who assign weekly capacities according to their project's metrics, and un-informed planners, who assign a constant capacity for the whole project or assign the capacity through random guessing (ibid.). Informed planners, on the other hand, positively affect project performance simultaneously for cost and schedule. They also pay close attention while monitoring the execution of tasks to follow up with their project's metrics and to study the effect of their assigned capacities (ibid.)

Several attempts were to develop tools that implement Lean Construction concepts like LPS, e.g. the Integrated Production Scheduler that aims to achieve quality, timeliness, and transparency (Chua, Jun, and Hwee 1999). A prototype called LEWIS assisted in making plans more reliable and assignments more constraint-free (Sriprasert and Dawood 2002). Newer methods of planning employed computer simulation (Song and Eldin 2012; Taghaddos et al. 2012). Song et al. (2012) developed an adaptive real-time tracking and simulation to enhance the look-ahead phase of LPS.

## Takt time planning

Takt is a German word that translates to ‘beat’ or ‘rhythm’. In general, Takt is defined as a set of intervals between successive events, where the period of intervals is the Takt time (Haghsheno et al. 2016). In construction it can be defined as the productivity rate that all activities should have to perform them at the same pace (Yassine et al. 2014). In manufacturing a fixed assembly line exists on which products move from one process to another. The existence of such assembly line helps measuring process cycle time, and consequently visualizing the pace of the process and comparing it to Takt, i.e. the rate at which the customer demands a certain product. But construction does not have a fixed assembly line. Rather workers and crews are the ones moving through the product - the site itself. To reach the clarity of assembly lines, construction processes should be planned with continuity between locations. For example in high-rise buildings Takt is the time for each operation to move from one floor to another.

Hence the process of creating a Takt plan and schedule in construction can become similar to manufacturing. Several Takt planning methods were developed (Fiallo C. and Howell 2012; Yassine et al. 2014; Binniger, Dlouhy, and Haghsheno 2017; Tommelein 2017). Such methods exhibited similarities in their steps, including identifying tasks, dividing working areas into zones, calculating the required Takt time, and levelling the workload to match the Takt time.

## Methodology

This study presents a method for quick adjustment during execution to evaluate project progress. Its proactive approach uses actual task progress to forecast PPC and derive preventive measures. Such improvement should be based on reliable values of production rates by linking required improvements to PRI. Risks of cascading delays or congestion from reallocating resources can be detected. A numerical example demonstrates the functionality for different performance scenarios. It helps project participants in monitoring their crews ahead of time, and thus make their promises more reliable. Finally, an evaluative metric is developed to assess the overall weekly progress.

Design Science Research (DSR) is the research methodology for this study. In construction management DSR can be a proper tool when building problem-solving artefacts that tackle real problems. It is considered constructive research that connects research and practice (Rocha, Formoso, and Tzortzopoulos-fazenda 2012), which this is the objective of this paper. Integrating LPS with singularity functions produces a tool to monitor actual activities on the WWP in practice. This will enable improving and (nearly) optimizing performance before the end of the week of execution. A numerical example will validate the proposed approach. The example will be analyzed under two scheduling techniques, LBS and TTP.

The approach compares planned and actual values of task progress. Forecasted data are taken from the WWP or a schedule over any time interval (daily, weekly, biweekly), while field personnel collect data on the actual progress. In graphical form it shows deviations and the required increase in production rates to improve the progress by the end of the week.

Singularity functions facilitate visual monitoring and automatic improvement in numerical form.

## Singularity functions for monitoring and performance improvement

This research focuses on metrics like PPC and PRI to prevent deviations from a plan. It emphasizes controlling and not scheduling, so the base plan is assumed to already be done and near optimal. Whether CPM or LBS is used, the process starts by entering the base plan for the WWP. This includes activities and their planned start and end times, quantity of work to be done, and the number of workers executing it. If TTP is used, the Takt production rate is inserted instead of the planned end date. From these inputs, the singularity functions forecast the activity progress.

The next step in the process is site personnel recording actual activity progress. This can be done daily during the execution of the activity, or for the first three days of each week to leave some time for improvements if needed. Only three inputs are needed to establish the singularity functions: The time that the activity actually started, the time at which the data was taken, and the work done until that moment. The singularity function calculates the predicted finish from the actual productivity of the crew. Future cascading delays can be detected as the difference between forecasted and planned progress if an activity is behind schedule and may affect its succeeding activities.

Singularity functions can quantify the needed improvement in the production rate to finish at a desired time. For example, for an activity with a planned duration of 4 days and required work of 4 units, the following improvement using singularity functions can be done as shown in Figure 1 per Equations 2 and 3.

Actual work without improvement  $W_n(t)$

$$= 0 \cdot \langle t - 0 \rangle^0 + 0.5 \cdot \langle t - 0 \rangle^1 - 0.5 \cdot \langle t - 8 \rangle^1 - 4 \cdot \langle t - 8 \rangle^0 \quad (2)$$

Actual work with improvement  $W_n(t)$

$$= 0 \cdot \langle t - 0 \rangle^0 + 0.5 \cdot \langle t - 0 \rangle^1 + 1 \cdot \langle t - 2 \rangle^1 - 3/2 \cdot \langle t - 4 \rangle^1 - 4 \cdot \langle t - 4 \rangle^0 \quad (3)$$

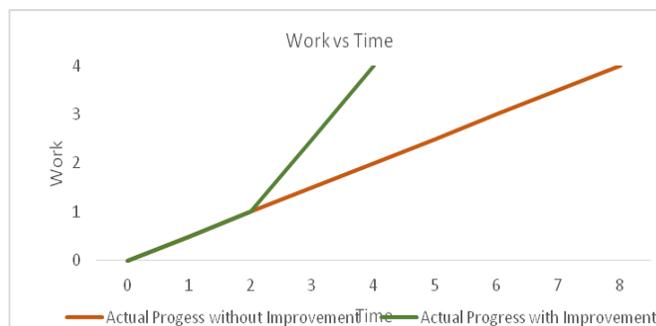


Figure 1 Graphical example of actual progress with and without improvement

(Gonzalez, Alarcón, and Mundaca 2008) suggested the process reliability index (PRI), which measures planning effectiveness from a commitment view. It is calculated for an activity by dividing actual by forecasted production rate per Equation 4.

$$\text{PRI} = \text{Actual Production Rate} / \text{Forecasted Production Rate} \quad (4)$$

As assumed herein, PRI is most effective if the base plan is already optimized. The PRI is supposed to make planning more reliable. Each crew has a normal production rate and a maximum production rate that reflects its capacity. To ensure that the crew can execute an improvement calculated by the singularity function, the required improved production rate is compared with the maximum. Per Equation 5 the modified maximum production rate is the maximum production rate multiplied by PRI. Thus, each crew's reliability in their production rates is considered.

$$\text{Modified Maximum Production Rate} = \text{Maximum Production Rate} \cdot \text{PRI} \quad (5)$$

Then Equation 6 informs whether the crew is able to finish or must allocate extra workers.

$$\text{Allocated Workers} = (\text{Required Improved Production Rate} / \text{Productivity}) - \text{Current Number of Workers} \quad (6)$$

Congestion in construction can occur in work areas where the number of workers is more than the area can hold (Koskela 1999). It leads to a decrease in productivity and safety on site. Therefore, the model gives an alert to notify of such congestion risk. Congestion can occur if the number of workers needed to complete the activity on time exceeds the acceptable limit. The acceptable density is determined by the user as model input in workers per m<sup>2</sup>.

It is now possible to calculate the percent task complete (PTC) of the activity that will help in forecasting PPC. The PTC is the ratio of work done at any time to total work needed to be done. Once PTC is calculated, the functions can calculate when the activity will reach 100% PTC, and thus it can be counted toward PPC as one of several inserted activities. Note how with few inputs into the model can give users the ability to forecast PPC at mid-week. The importance of this forecast is twofold: To identify an activity that is preventing PPC from reaching the desired value, and to be proactive and take corrective measures so that the actual PPC at the end of week increases.

Lastly, the new metric is the Percent Improvement Complete (PIC). It is measured at the end of the execution week to quantify the crew's reliability in completing the activities that needed improvement during the week. It essentially measures the reliability of the promises that were made during the week of execution: It is the ratio of the number of activities that required improvement and were actually completed at the required end time, to all those that required improvement (regardless of completion). The new PIC can be used to assess the capability of the control system to apply required improvements to activities' production rates by removing constraints on the spot.

$$\text{PIC} = \text{Number of Activities That Needed Improvement and Were Completed} / \text{Number of All Activities That Needed Improvement} \quad (7)$$

Expressed in LPS terms, PIC = Did Improve & Complete / Should Improve as its definition.

## Application example

An example is analyzed to test the approach. A five-story building project consists of sequential activities A, B, and C. For simplicity, the example is applied to a WWP. The area of each floor is 300 m<sup>2</sup> and the working area is 50 m<sup>2</sup>. Inputs and outputs are labeled in Table 2 and Table 3 for LBS and TTP scheduling methods, respectively.

**Table 2 Program Input and Output per Activity for LBS**

Item	Input	Output
Forecast Activity Data	Start time - End time - Work to be done	Planned production rate
Actual Activity Data (so far)	Actual start time - End time before improvement - Work done so far	Actual production rate - PRI - Warning of cascading delays - Prediction of metrics
Improvement of Activity	Required end time	Required improved production rate
Resources Data	Number of workers - Maximum production rate - Working area - Congestion limit	Modified maximum production rate - Warning if resource allocation is needed - Congestion warning

**Table 3 Program Input and Output per Activity for TTP Scheduling**

Item	Input	Output
Forecast Activity Data	Start time - Work to be done - Takt Time production rate	Planned end date
Actual Activity Data (so far)	Actual start time - End time before improvement - Work done so far	Actual production rate - PRI - Warning of cascading delays - Prediction of metrics
Improvement of Activity	Time to return to Takt schedule	Required improved production rate "Improvement PR to Takt"
Resources Data	Number of workers - Maximum production rate - Working area - Congestion limit	Modified maximum production rate - Warning if resource allocation is needed - Congestion warning

The output is calculated with singularity functions. For activity A with a duration of 3 days (from day 0 to day 3) in an LBS, 5 units must be done. Work started at day 0 and 2.5 units were completed until day 2 (actual production rate = 1.25 units/day). To finish the activity at day 3, the required improved production rate must be 2.5 units/day.

Actual work without improvement WA(t)

$$= 0 \cdot \langle t - 0 \rangle^0 + 1.25 \cdot \langle t - 0 \rangle^1 - 5 \cdot \langle t - 4 \rangle^0 - 1.25 \cdot \langle t - 4 \rangle^1 \quad (8)$$

Actual work with improvement WA(t)

$$= 0 \cdot \langle t - 0 \rangle^0 + 1.25 \cdot \langle t - 0 \rangle^1 + (2.5 - 1.25) \cdot \langle t - 2 \rangle^1 - 5 \cdot \langle t - 4 \rangle^0 - 2.5 \cdot \langle t - 4 \rangle^1 \quad (9)$$

Results for B show that the actual progress will cause a cascading delay. All activities must be accelerated to be completed on time. After inserting the maximum production rate, it is modified by the PRI for the current number of workers in the crew. All activities deviate from their plan; thus, maximum production rates are reduced. Activities B and C require extra resource allocation, while the crew for A is sufficient. Moreover, congestion is detected in B if the required number of workers is added. This shows that the required production rate cannot be implemented, so its finish time must be extended. Figure 2 shows the planned, actual, and ultimately improved progress for A, B, and C.

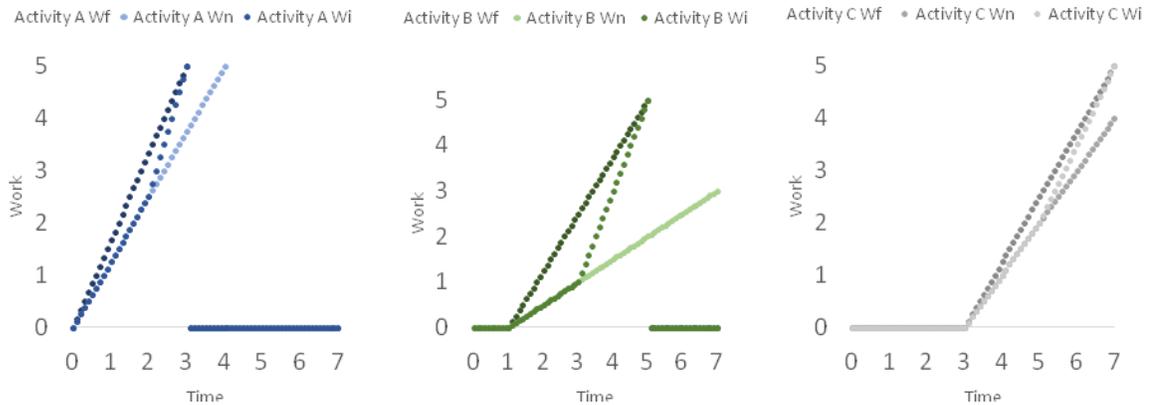


Figure 2 Forecasted, Actual, and Improved Progress for Activities A, B, and C respectively in LBS

PPC is forecasted before the end of the week, so that the crews can proactively improve their progress (Table 4).

Table 4 Forecasted PPC before improvements

Actual with Improvement	MAX PTC at End of WWP	Status at End of WWP	# of Tasks on WWP	PPC
A	100	100		
B	60	60	3	33%
C	80	80		

The actual value of PPC is also calculated for the end of the execution week (Table 5).

Table 5 Actual PPC after improvements

Actual with Improvement	MAX PTC at End of WWP	Status at End of WWP	# of Tasks on WWP	PPC
A	100	100		
B	100	100	3	100%
C	100	100		

And PIC shows that only 67% of activities that were supposed to be improved were actually completed (Table 6).

Table 6 PIC value

# of Tasks that need Improvement	# of Tasks that need Improvement + can be completed	Percent Improvement Complete (PIC)
3	2	67%

Another example can be applied on a TTP schedule, where the planned and improved activity progresses are linked to Takt time. The user specifies the required start time, Takt time production rate, and work to be done. Then the actual start time, end time just before improvement, and work done so far are inserted. The actual production rate is calculated. If the actual production rate is different than the Takt time production rate, the user specifies the ‘time to Takt’ i.e. the time that will be spent before the actual progress converges to Takt progress. Afterward the progress should proceed per the planned Takt progress. If the actual production rate is lower than the Takt time production rate, it must be increased. Else if it is higher, it must be decreased.

For activity A with 5 units of work to be done and a planned duration of 6 days (from day 0 till day 6), the following singularity functions for the actual work without and with improvement are shown by functions 10 and 11 respectively.

Actual work without improvement WA(t)

$$= 0 \cdot \langle t - 0 \rangle^0 + 0.5 \cdot \langle t - 0 \rangle^1 - 5 \cdot \langle t - 10 \rangle^1 - 0.5 \cdot \langle t - 4 \rangle^0 \quad (10)$$

Actual work with improvement WA(t)

$$= 0 \cdot \langle t - 0 \rangle^0 + 0.5 \cdot \langle t - 0 \rangle^1 + (1.49 - 0.5) \cdot \langle t - 2 \rangle^1 - (1.49 - 0.83) \cdot \langle t - 3 \rangle^1 - 5 \cdot \langle t - 6 \rangle^0 - 0.83 \cdot \langle t - 6 \rangle^1 \quad (11)$$

An example of activities A, B, and C is shown in Figure 3. Activities A and C show low actual production rates, while activity B shows a high actual production rate.

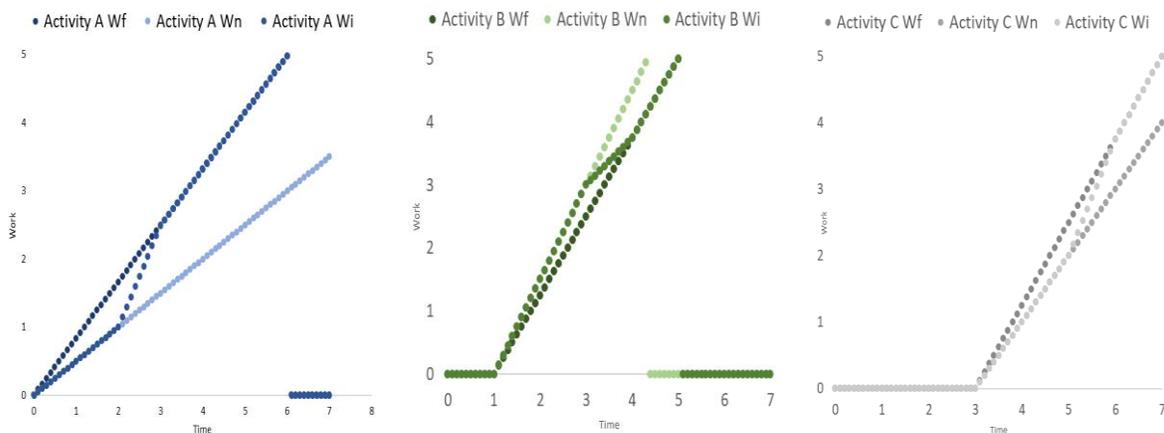


Figure 3 Forecasted, Actual, and Improved Progress for Activities A, B, and C respectively in TTP Scheduling

## Conclusion and future research

This paper has presented an approach to monitor project performance at the level of the WWP of LPS, or any other preferred level. Previous research has used singularity functions to solve linear schedules. This study expands them to forecast and control activity progress. It offers a user-friendly tool that fits within existing LPS philosophy and whose graphical output is simple enough for most site personnel to understand. An example has validated the accuracy in calculating useful output, subject of course to the quality of the input data. It can be applied to monitor and control progress based on CPM, LBS or TTP schedules. Moreover, it does not have limitations on the number of activities that can be entered.

Several LPS metrics are used in this study. PPC is forecasted from actual activity progress during the execution week to show early signs of the reliability of the look-ahead planning. The second metric is the PRI, which serves a modification factor for the maximum production rate to calculate the resource allocation. A new metric has been introduced, the PIC for the reliability to implement required improvements during execution. It is recommended that PIC is used alongside the maximum production rates that are modified by PRI to ensure that the required improvements are rational and within the crew's capacity. While PPC shows the reliability of the promises made at the level of the WWP, PIC shows the reliability of the promises made during the week of execution for which the improvements were promised to be done.

Additional metrics could be developed to show the volume of improvement that was done as the difference between old and new production rates for each activity to link them with the percent of completion. Such metrics may further refine the assessment of production rates. The new approach should be tested on actual project to validate the results. Further development could transform the proposed computer tool into an interactive mobile application of lean concepts to support process monitoring and controlling.

## References

- Abou-Ibrahim, Hisham, Emile Zankoul, Farook Hamzeh, and Lynn Rizk. (2019). "Understanding the Planner's Role in Lookahead Construction Planning." *Production Planning & Control* 30 (4): 271-284.
- Alarcón, Luis F., and R Calderón. (2003). "A Production Planning Support System for Construction Projects." *International Group for Lean Construction* 11: 1-13.
- Ballard, Glenn, and Gregory Howell. (2003). "An Update on Last Planner." In: *Annual Conference of the International Group for Lean Construction, 11, 2003, Blacksburg, 1-10*.
- Beer, F. J., E. R. Johnston, J. T. DeWolf, and D. F. Mazurek. (2014). *Mechanics of Materials*. 7th Editio. McGraw-Hill, New York.
- Binner, Marco, Janosch Dlouhy, and Shervin Haghsheno. (2017). "Technical Takt Planning and Takt Control in Construction." In *25th Annual Conference of the International Group for Lean Construction, 605-612*.
- Chitla, V.R., and T.S. Abdelhamid. (2003). "Comparing Process Improvement Initiatives Based on Percent Plan Complete and Labour Utilization Factors." *Proceedings of the 11th Annual Conference of the International Group for Lean Construction*.
- Chua, Dkh, Sl Jun, and Bs Hwee. (1999). "Integrated Production Scheduler for Construction Look-Ahead Planning." *7th Annual Conference of the International Group for Lean Construction, (IGLC-7), 287-298*.
- Fiallo C., Mario, and Gregory A. Howell. (2012). "Using Production System Design and Takt Time to Improve Project Performance." In *20th Annual Conference of the International Group for Lean Construction, 1-10*.
- Formoso, Carlos T, and Camile B Moura. (2009). "Evaluation of the Impact of the Last Planner System on the Performance of Construction Projects." In *Proceedings of the 17th Annual Conference of the International Group for Lean Construction, 153-164*. International Group for Lean Construction (IGLC).
- Gonzalez, V., Luis F. Alarcón, and F. Mundaca. (2008). "Investigating the Relationship between Planning Reliability and Project Performance." *Production Planning and Control* 19 (5): 461-474.
- Haghsheno, Shervin, Marco Binner, Janosch Dlouhy, and Simon Sterlike. (2016). "History and Theoretical Foundations of Takt Planning and Takt Control." *International Group for Lean Construction, 53-62*.
- Hamzeh, Farook, Glenn Ballard, and Iris D. Tommelein. (2008). "Improving Construction Work Flow - The Connective Role of Lookahead Planning." *16th Annual Conference of the International Group for Lean Construction, (IGLC-16), 635-646*.
- Hamzeh, Farook, Glenn Ballard, and Iris D. Tommelein. (2009). "Is the Last Planner System Applicable to Design?—A Case Study." In *17th Annual Conf. of the International Lean Construction Group, 165-176*. Taipei, Taiwan.
- Hamzeh, Farook, Glenn Ballard, and Iris D. Tommelein. (2012). "Rethinking Lookahead Planning to Optimize Construction Workflow." *Lean Construction Journal, 15-34*.
- Isaac, Shabtai, Yi Su, Gunnar Lucko, and David Dagan. (2017). "Work-Path Modeling and Spatial Scheduling with Singularity Functions." *Journal of Computing in Civil Engineering* 31 (4): 04017008-1-14.

- Koskela, Lauri. (1999). "Management of Production in Construction: A Theoretical View." *7th Annual Conference of the International Group for Lean Construction*, 241-252.
- Liker, J. K. (2004). *The Toyota Way - 14 Management Principles from the World's Greatest Manufacturer*. McGraw Hill, NY.
- Lucko, Gunnar. (2007). "Computational Analysis of Linear and Repetitive Construction Project Schedules with Singularity Functions." *Computing in Civil Engineering*, 9-17.
- Lucko, Gunnar. (2009). "Productivity Scheduling Method: Linear Schedule Analysis with Singularity Functions." *Journal of Construction Engineering and Management* 135 (4): 246-253.
- Lucko, Gunnar. (2010). "Modeling Resource Profiles with Singularity Functions." *Construction Research Congress 2010: Innovation for Reshaping Construction Practice.*, 1165-1174.
- Lucko, Gunnar, and James P. Cooper, III. (2010). "Modeling Cash Flow Profiles with Singularity Functions." In *Construction Research Congress 2010*, 1155-1164. Reston, VA: American Society of Civil Engineers.
- Lucko, Gunnar, Hisham M. Said, and Ahmed Bouferguene. (2014). "Spatially-Constrained Scheduling with Multi-Directional Singularity Functions." In *Construction Research Congress 2014: Construction in a Global Network*, 1148-1457.
- Nahmias, S., and Y. Cheng. (2009). *Production and Operation Analysis*. 6th Editio. McGraw-Hill, New York.
- Nguyen, Thi Qui, and Sharath Sridhar Waikar. (2018). "A Relook at Plan Reliability Measurements in Lean Construction and New Metrics From Digitized Practical Implementation." *26th Annual Conference of the International Group for Lean Construction*, 1037-1046.
- Oakland, J., and M. Marosszeky. (2017). *Total Construction Management: Lean Quality in Construction Project Delivery*. Routledge.
- Rocha, Cecilia G, Carlos T Formoso, and Patricia Tzortzopoulos-fazenda. (2012). "Design Science Research in Lean Construction: An Analysis of Research Processes and Outcomes." *Proceedings for the 20th Annual Conference of the International Group for Lean Construction*, 20: 1-14.
- Samad, Ghali El, Farook Hamzeh, and Samir Emdanat. (2017). "Last Planner System - the Need for New Metrics." *25th Annual Conference of the International Group for Lean Construction II* (July): 637-644.
- Seppänen, Olli. (2013). "A Comparison of Takt Time and LBMS Planning Methods." *International Group of Lean Construction*, 727-738.
- Song, Linguang, and Neil N. Eldin. (2012). "Adaptive Real-Time Tracking and Simulation of Heavy Construction Operations for Look-Ahead Scheduling." *Automation in Construction* 27: 32-39.
- Sriprasert, E, and N Dawood. (2002). "Next Generation of Construction Planning and Control System: The LEWIS Approach." *EWork and EBusiness in Architecture, Engineering and Construction: Proceedings of the Fourth European Conference on Product and Process Modelling in the Building and Related Industries*, 1-12.
- Su, Yi, and Gunnar Lucko. (2016). "A Unified Quantitative Model for Project Management with Singularity Functions," 2019-2028.
- Taghaddos, Hosein, Ulrich Hermann, Simaan AbouRizk, and Yasser Mohamed. (2012). "Simulation-Based Multiagent Approach for Scheduling Modular Construction." *Journal of Computing in Civil Engineering* 28 (2): 263-274.

- Tommelein, Iris D. (2017). "Collaborative Takt Time Planning of Non-Repetitive Work." *25th Annual Conference of the International Group for Lean Construction*, no. July: 745-752.
- Yassine, Tarek, Mohammad Bassel, Saleh Bacha, Farah Fayek, and Farook Hamzeh. (2014). "Implementing Takt-Time Planning in Construction To Improve Work Flow." *International Group of Lean Construction*, 787-798.

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