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THE WIP-PUSH-WAVE: A LEADING INDICATOR FOR PROJECT PRODUCTION CONTROL

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ABSTRACT

Project management has traditionally depended on lagging indicators, such as the 'Earned Value', that provide retrospective feedback and support reactive decision-making. In contrast, leading indicators that monitor production conditions and enable proactive control have been proposed in the Lean Construction body of knowledge. Metrics such as Percent Plan Complete (PPC) and subsequent flow-based measures have advanced this shift toward assessing workflow reliability and production status rather than after-the-fact outcomes. This paper introduces the WIP-Push-Wave (WPW), a novel leading indicator that captures and visualizes the wave effect created as Work in Progress (WIP) accumulates and rolls forward across planning cycles. By quantifying the degree to which the planned WIP exceeds the demonstrated capability of the production system, the WPW reveals overload conditions as they emerge, allowing intervention before performance losses occur. We present a case study of a portfolio of 1,300 projects, demonstrating the recurring wave phenomenon where unfinished work rolls forward, inflating WIP and degrading performance. We interpret this pattern as a self-reinforcing feedback loop driven by overcommitment and optimism bias in planning, and propose that a balancing loop, grounded in production principles, is needed to break this cycle and prevent such waves from forming. The WPW enables managers to identify planning biases, guiding them to improve the planning process.

KEYWORDS

Leading indicators, optimized cycle-time flow, portfolio management, production planning and control.

INTRODUCTION

Project planning and control in construction remains dominated by methods such as the Critical Path Method (CPM) and Earned Value Management (EVM), which use lagging indicators that reveal problems retrospectively. In most cases these indicators rely solely on a narrow dimension, evaluating time and measured direct cost performance, while neglecting forward-looking measures (Shenhar et al., 2001). From a system dynamics perspective, dependence on lagging indicators traps project teams in a reinforcing feedback loop, "chasing one's own tail". Breaking these cycles requires a different perspective, monitoring the conditions of production in real time with leading indicators, rather than recording deterministic outcomes (Bertelsen 2003; Lyneis and Ford 2007; Sterman 2000). Leading indicators may provide early warnings

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of production problems so that they can be dealt with proactively; While several indicators monitor planning reliability (e.g., PPC), fewer capture excessive WIP loading, despite its impact on system performance (Bashford et al. 2005). This paper introduces the WIP-Push-Wave (WPW), a novel leading indicator that reveals how incomplete work rolls forward across reporting cycles, creating a backlog wave of uncompleted tasks.

The WPW is measured as the percentage of planned WIP that exceeds the demonstrated capability of the system, thereby signalling when workloads pass the system's capacity to process them effectively. By making this visible, the WPW indicator allows managers to detect unhealthy conditions before they result in performance loss. The WPW indicator was developed as part of an ongoing effort to develop and implement the Optimized Cycle-Time Flow (OCF) strategy within Intel. OCF is a strategy for Project Portfolio Management (Pemberton 2018) that has been applied in over 2,000 projects (Gabai et al. 2023, 2024; Gabai and Sacks 2020). OCF was originally developed for construction management in multiple semiconductor plants, each comprising thousands of projects. It strives to improve organizational TH, by reducing CT at the single project level, while levelling the WIP at the portfolio level, and thus reducing time to market for new production lines in a Fab.

We demonstrate the implementation of the WPW on a portfolio of 1,300 projects, revealing a recurring wave phenomenon, in which unfinished work rolls forward, inflating WIP and degrading performance. The WPW phenomena reflects the fundamental planning fallacy of overcommitment. It exposes an optimism bias embedded in the planning process (Kahneman and Tversky 1979), as managers assume future performance will align with desired outcomes rather than demonstrated historical evidence.

LITERATURE REVIEW

LAGGING VS. LEADING INDICATORS IN PROJECT CONTROL

Management science distinguishes between lagging indicators, which measure outcomes that have already occurred, and leading indicators, which provide predictive signals of emerging risks (see table 1). Lagging indicators based on the Earned Value Method (EVM), such as Schedule Variance (SV) and Cost Variance (CV), provide accountability, yet they trap project teams in cycles of retrospective detection and do not enable timely responses. Kim and Ballard (2000, 2010) explain that this limitation is rooted in the "Managing by Results" mindset underlying EVM, which focuses on outcome metrics while ignoring production interdependencies and workflow reliability. In contrast, "Managing by Means" emphasizes production flow, constraint removal, and reliability. Leading indicators align with "Managing by Means" logic, monitoring the conditions of production to enable proactive action.

Table 1: Comparison between lagging and leading indicators

	Lagging Indicators	Leading Indicators
Definition	Measure outcomes after they occur	Measure current production conditions
Focus	Accountability and reporting	Proactive control and prediction
Typical Metrics	Schedule Variance (SV), Cost Variance (CV)	Percent Plan Complete (PPC)

PLANNING-ORIENTED LEADING INDICATORS

The Last Planner System (LPS) introduced a paradigm shift by embedding leading indicators of planning reliability into construction management practice. Ballard (2000) proposed Percent

Plan Complete (PPC) as a weekly measure for reliability. Unlike the EVM, which measures work completed regardless of its influence on downstream flow (Kim and Ballard 2000, 2010), PPC evaluates the reliability of planning commitments and provides short-cycle feedback loops for improvement.

A comprehensive PPC implementation includes the recording and examination of reasons for non-ready and incomplete tasks. However, in most projects the "make ready" aspects of LPS are implemented weakly, if at all. To address this limitation, Hamzeh et al. (2012, 2019) advanced LPS metrics further by proposing measures of task readiness, causes of failures, and the overall quality of planning. Additionally, Jang and Kim (2008) developed Percent Constraints Removed (PCR) as a measure of how effectively constraints are removed before execution. Together, these indicators represent an ongoing effort that began with measuring planning reliability and continues to evolve towards a holistic evaluation of the production system.

PRODUCTION-ORIENTED LEADING INDICATORS

Another stream of research, built on Factory Physics (Hopp and Spearman 1996), advanced leading indicators that capture real-time health of production, emphasizing the fundamental flow metrics: WIP, CT, and TH. Grounded in Little's Law (Little 1961), the relationship TH = WIP / CT demonstrates that excessive WIP not only extends CT but may also decrease the TH as more waste enters the production system (Bashford et al. 2005; Koskela and Howell 2001). Building on this, Sacks et al. (2017) proposed the Construction Flow Index (CFI), a metric for quantifying the smoothness of production using time–location data, embedding WIP and TH into a single flow metric. Later, Murguia et al. (2023) provided evidence that flow measures (e.g. batch size and WIP levels) can explain significant variation in construction productivity.

Another stream of research leverages the Line of Balance (LOB) and Location-Based Management Systems to monitor flow visually. Kenley and Seppanen (2010) demonstrated that flowline charts can reveal mismatches in production rates (when lines converge or intersect), indicating potential bottlenecks or trade conflicts. These visual tools emphasize synchronization of rates across phases and trades, underscoring the importance of balanced flow.

Planning-oriented indicators are well established and inherently forward-looking, while production-oriented metrics typically reflect the current state of the system. Yet current production conditions directly influence future performance, indicating a missing linkage between production metrics and planning control. The WPW is proposed as a step toward addressing this gap, building on empirical observations and the theoretical interpretation of these dynamics across planning cycles

OPTIMIZED CYCLE-TIME FLOW (OCF)

The development of the WPW index is rooted in the broader Optimized Cycle-Time Flow (OCF) strategy, which was designed to support production flow in Intel's multi-project tool-installation portfolios.

The OCF strategy is built upon Lean Construction (LC) theories, particularly the Portfolio, Process, and Operations (PPO) model (Sacks 2016). It focuses on flow and value within Project Portfolio Management (PPM) and multi-project organizations, integrating seven principles derived from core theories and methodologies that are reinforced and synergized once combined.

The OCF flywheel (Figure 1) begins with Principle I – 'Plan and Integrate Strategically' and Principle II – 'Plan Tactical Targets', both rooted in Strategic Project Leadership® (SPL) (Shenhar 2015). These principles emphasize business-driven strategic planning, incorporating

Target Pull Plans to align each project with CT reduction targets and eventually optimize TH at the portfolio level.

Principle III – 'Collaborate' aligns with the LPS (Ballard 2000), emphasizing collaborative planning to improve workflow reliability and production stability. Principle IV – 'Resolve Constraints', and Principle V – 'Restructure Resources' are based on the Theory of Constraints (TOC) (Goldratt and Cox 2004), focusing on identifying and removing bottlenecks (whether physical or informational) that limit the production system (Ballard and Tommelein 2016). Principle VI – 'Control Project Start' and Principle VII – 'Ensure Project Flow' are rooted in the Toyota Production System (TPS) (Liker 2001), utilizing a pull-based approach where projects are initiated just-in-time (JIT) based on readiness, demonstrated resource capabilities, and client demand. This structured batching of projects enables controlled WIP levels, facilitating CT reductions at both project and portfolio levels.

Figure 1: The OCF flywheel (Credit: Intel Corporation).

Previous research has highlighted various aspects of OCF: Gabai and Sacks (2020) introduced the foundational principles of OCF, demonstrating its ability to significantly reduce cycle times. Gabai et al. (2023) extended this by illustrating the scalability of OCF across facilities and project domains, emphasizing its repeatable and consistent implementation. Gabai et al. (2024) demonstrated how doubling of throughput is achieved at the single project level, providing a case study that validates the empirical data. This paper adds another tire in the ongoing effort for the development and communication of OCF.

RESEARCH METHOD

The study follows the Design Science Research (DSR) methodology (Gregor and Hevner 2013; Scott and Gibbons 2001; Van Aken 2005), which provides a structured framework for developing and evaluating innovative artifacts that address practical problems. DSR is inherently iterative, involving four key phases: (1) problem identification, (2) artifact development, (3) artifact evaluation in real-world settings (via case studies, action research, etc.), and (4) theory development and results communication.

In this research, the artifact is the WPW, a leading indicator that quantifies how unfinished work rolls forward across reporting cycles, creating a wave effect of accumulated WIP. The WPW has been developed and tested through application in several portfolios of Tool Installation (TI) projects in Intel semiconductor fab construction, and it is currently applied as a practical leading indicator in Intel.

The paper demonstrates the application of the WPW through a case study of a portfolio of 1,300 TI projects executed in the construction of a fab. This environment was relatively stable in terms of resource allocation and external constraints, enabling the analysis to focus on the dynamics that generate the WPW phenomenon. The data were extracted from a cloud-based planning system integrated with Primavera P6, which records planned inputs, project progress, and production outputs across the portfolio, enabling the estimation of demonstrated capability from historical production rates. TI projects involve installation of highly specialized semiconductor manufacturing tools, requiring meticulous integration of multiple trades, including extensive MEP work. The semiconductor environment is characterized by millimetre-level tolerances across the utility, sub-fab, and cleanroom levels (as presented in Figure 2), demanding close coordination among diverse trades working simultaneously in tightly constrained spaces. This environment serves as a compelling setting for developing and testing leading indicators for production control.

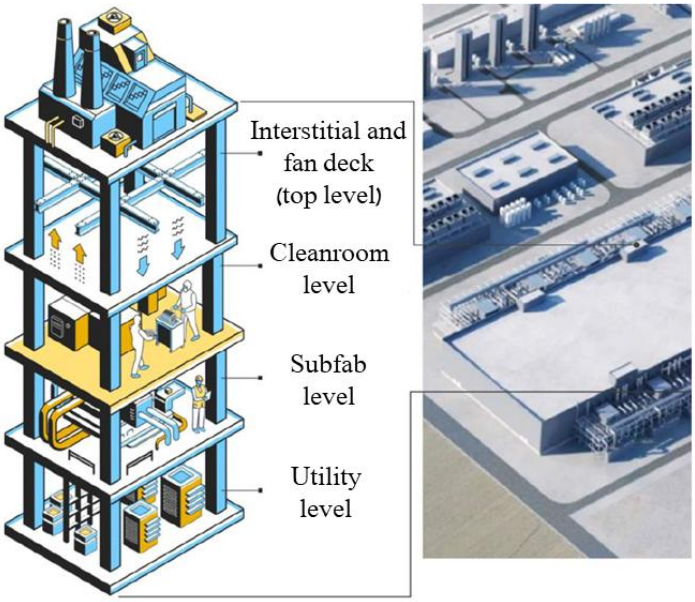

Figure 2: An illustration of the work locations in a semiconductor fab

CASE STUDY

The case study examines a portfolio of 1,300 projects, each comprising four construction phases. The implementation of the WPW is demonstrated on one of these phases. Performance was evaluated on a monthly cycle, using a Velocity Flow Capability (VFC) analysis, which compares the planned input with the demonstrated capability of each phase. We focused on a specific period in which the WPW emerged. During this period, Phase 1 consistently reached a steady production rate of 80 projects per month. This stable performance served as the baseline input for the subsequent phases, against which the Velocity Flow Capability (VFC) was measured. The demonstrated capability of each phase was estimated from the average production rates observed in the portfolio over the analysed period.

$$VFC\ [\%] = \frac{Demonstrated\ Capability}{Planned\ Input}$$

The VFC analysis reveals a sharp decline in production rate across phases. Phase 1 maintained a rate of 80 projects per month, while Phase 2 dropped to 54 projects per month

(68% of the 80 projects). The bottlenecks appeared in Phases 3 and 4, where production rates declined to 35 and 38 projects per month (44% and 48%), respectively.

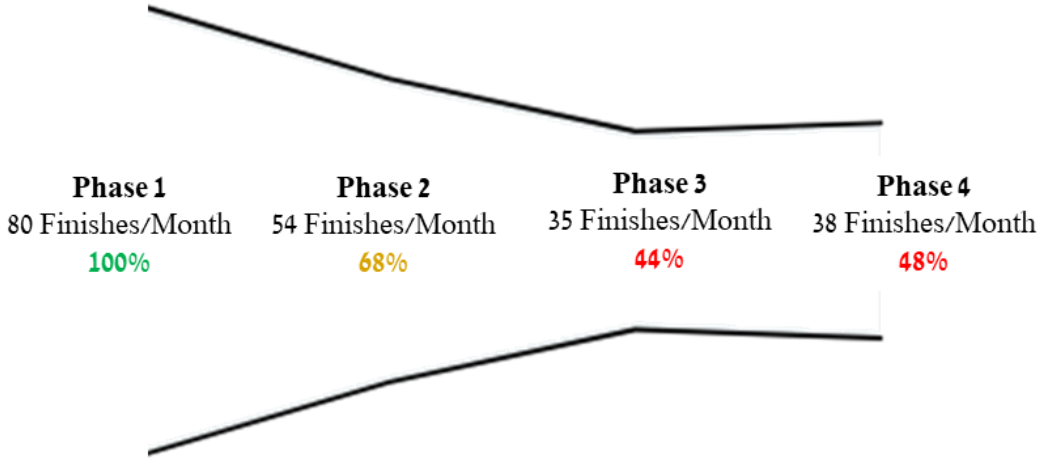

Figure 3: Velocity flow capability analysis for the case study

Phase 1 represents the core construction phase in each project. Historically, this phase was the primary bottleneck across most portfolios; however, following several years of thorough OCF implementation, the construction in Phase 1 was stabilized. As presented in the next section, the WPW revealed planning failures in the successive phases, which include testing and commissioning activities that require coordination with external suppliers. Previously, these phases were not expected to become bottlenecks and were therefore excluded from the scope of OCF implementation. The results highlight that while OCF successfully stabilized upstream construction phases, extending it downstream is essential to improve performance across the entire portfolio.

THE WIP-PUSH-WAVE (WPW)

The WPW measures the degree to which the planned workload exceeds the demonstrated capability during each planning cycle. It is defined as the ratio between the peak planned WIP and the demonstrated capability:

$$WPW\% = \frac{Planned\ WIP\ Peak}{Demonstrated\ Capability}$$

A higher WPW indicates a stronger push effect, where excessive planned WIP imposes pressure on the system and reduces the likelihood that the plan will be executed as planned. When the planned WIP peak repeatedly exceeds the demonstrated capability across planning cycles, it generates a wave phenomenon, as unfinished work rolls forward into subsequent cycles. Once formed, this wave gains inertia, enabling it to carry over across multiple planning iterations, and in some cases, throughout the entire duration of a project. In the case study, Phase 3 provides clear evidence of the WPW effect: although the demonstrated capability of this phase was only 35 finishes per month, the system was scheduled with much greater WIP.

Figure 4 illustrates the WPW for phase 3, across successive planning cycles. For example, in month 5 The WPW reaches a level of 331%, as the planned WIP reached a peak of 116 projects per month, compared to the demonstrated capability of 35 projects per month:

$$WPW_{Month\ 5}\% = \frac{116}{35} = 331\%$$

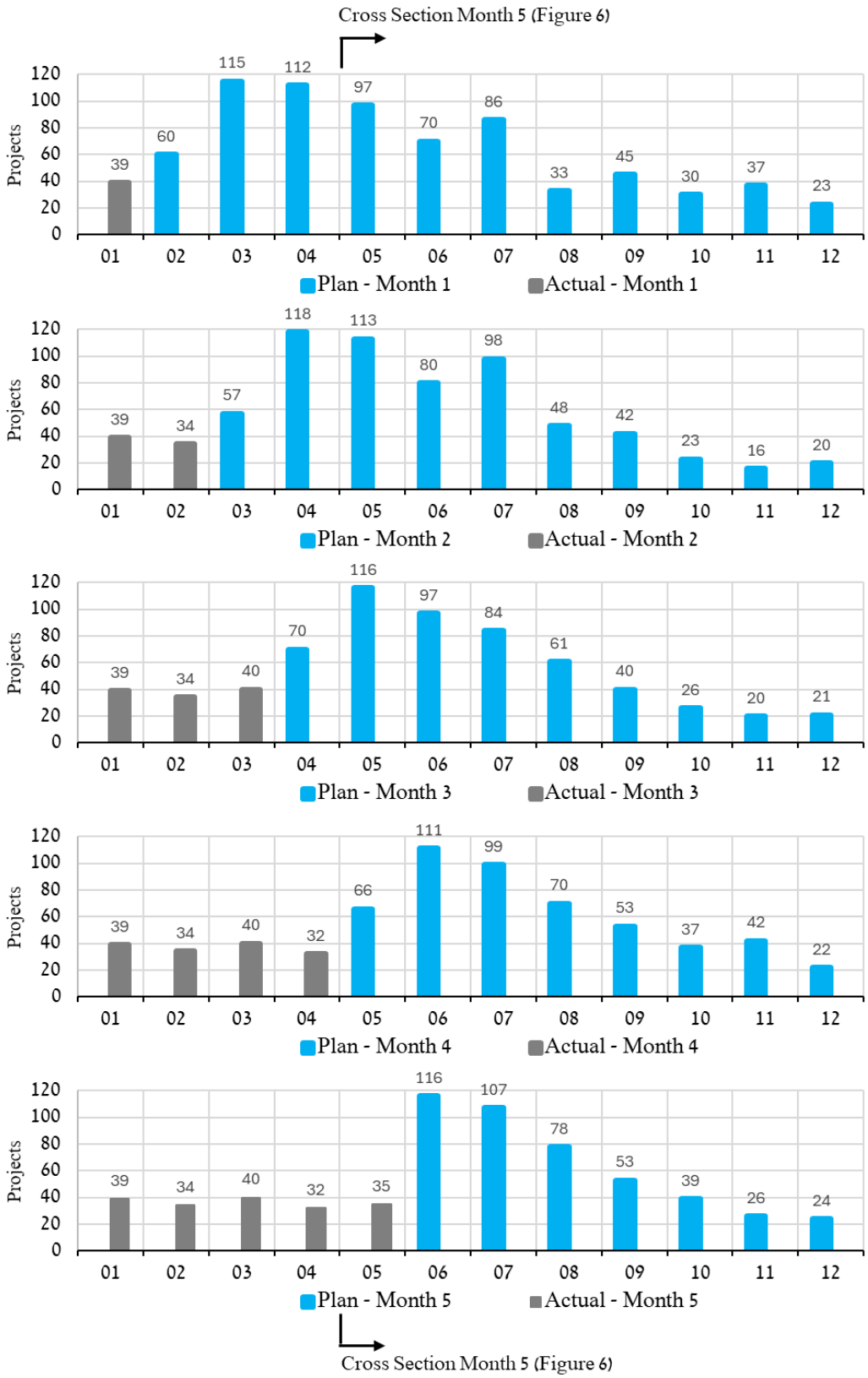

Figure 4: Planned WIP across successive planning cycles vs. actual performance in phase 3

Elevated WIP values may arise not only from planning bias, but also from uncertainty within the production system or from external factors that influence the complex dynamics of construction. Even in such cases, it is crucial to track the evolution of the WPW and mitigate its growth before it gains momentum and destabilizes the system. Unlike a typical production

line in a factory, where the physical capacity of a machine limits the number of units that can be processed, in a project environment, resources can be spread over more work packages than they can process efficiently. They thus become overwhelmed, and their productivity and production rate are reduced. These effects are exacerbated when the resources are applied to make projects ready, when most of those projects are in any case beyond the capacity of the system to perform even if they are ready.

Figure 5 illustrates the temporal dynamics of the WPW across successive planning cycles, where repeated overcommitments cause inflated WIP to move forward in time, creating recurring waves of unfinished work that undermine system stability. This figure is a superposition of the data present in figure 4, to illustrate the wave effect. Each shaded layer represents a successive planning cycle that re-scheduled unfinished work, creating the visible "push" effect.

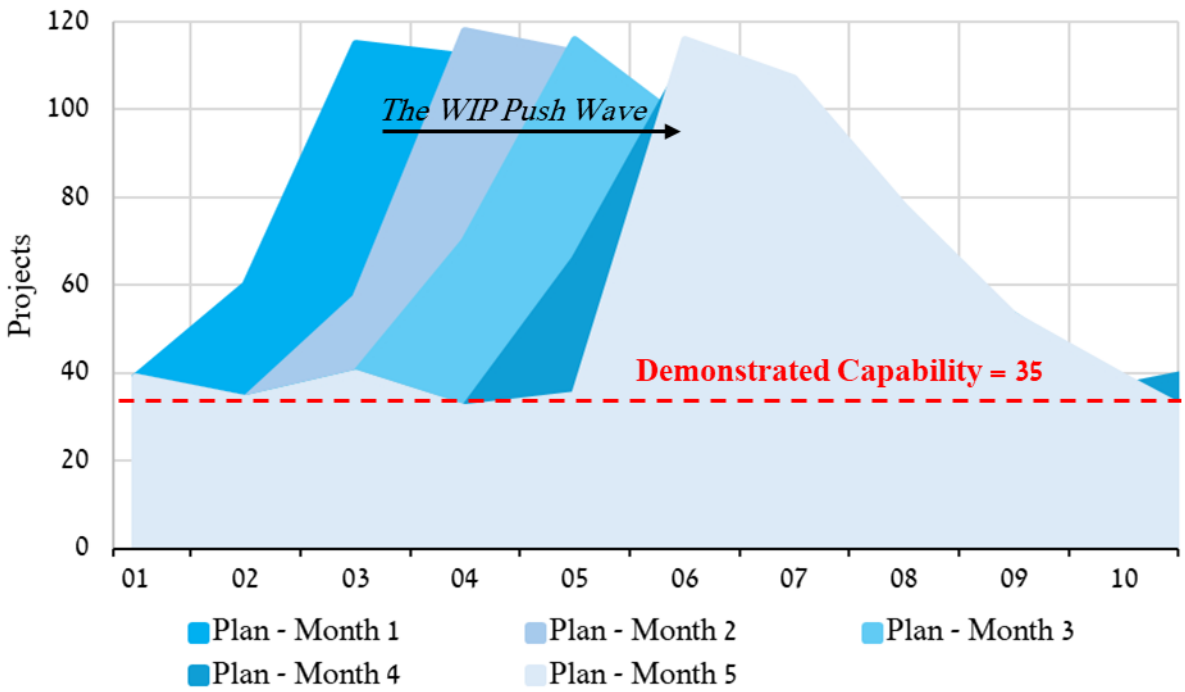

Figure 5: Illustration of the WPW vs. the demonstrated capability of phase 3

The WPW can also be visualised through the evolvement of the planned WIP for any specific month. For example, in the case of Month 5, Figure 6 shows how the plan evolved across successive planning cycles approaching that month. The planned workload reached a peak of 116 projects during Month 3. As execution came closer, it became evident that the planned workload was not feasible, and the planned WIP subsequently declined. The data for Month 5 itself represents the actual work completed, highlighting the dissonance compared to the earlier over-optimistic plans.

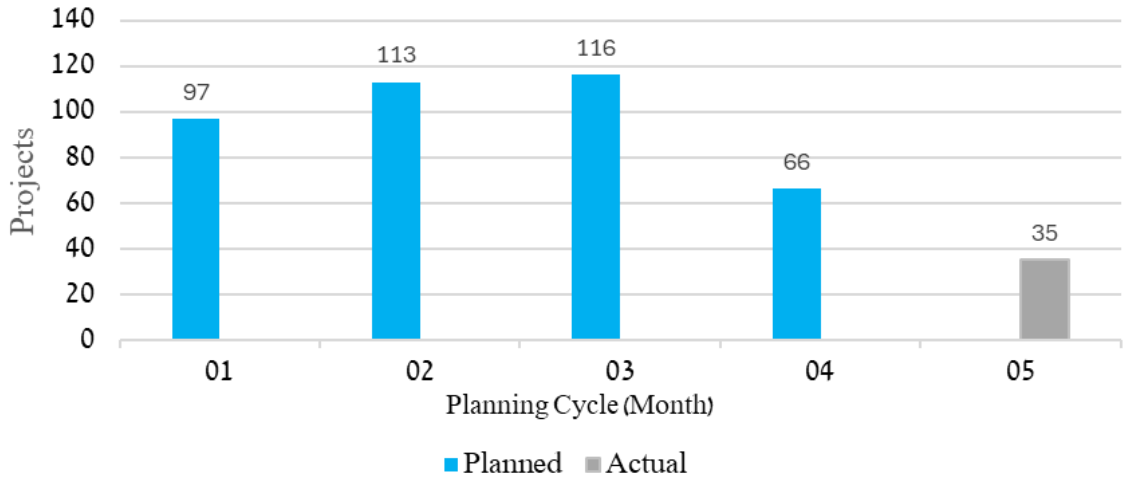

Figure 6: The WIP planned for month 5, across successive planning cycles - the cross section defined in figure 4 (note that only in month 5 did the plan recognize the actual capability).

DISCUSSION AND CONCLUSIONS

This study contributes to the ongoing effort to develop quantitative indicators for production control in construction. Earlier research established that monitoring and controlling the production conditions (via production indicators such as WIP, CT, and variability), is more effective than relying on cost or schedule lagging indicators. The WPW builds on this foundation by extending the scope of production-oriented leading indicators to evaluate the planning process and the production status, by quantifying how excessive WIP commitments can generate and sustain flow disruptions across successive planning cycles. The conceptual contribution of the WPW lies in revealing the "wave effect" that emerges when planned WIP repeatedly exceeds the system's demonstrated capability across planning cycles. By visualizing this dynamic, the WPW provides managers with an early warning signal to intervene and "lower the water level" before planning overload escalates. The WPW exposes a recurring planning fallacy is reflected in the persistent WIP accumulation patterns observed in Figures 4–6. This pattern reflects a tendency to assume that future cycles will absorb pending work despite clear evidence of capacity limits. If left unaddressed, the high "water level" may persist throughout the project's duration, undermining production stability, and sabotage effective lookahead planning and the make-ready process. Application of the WPW confirmed that OCF implementation in Phase 1 promoted stable and predictable production flow. This phase, which previously had been the primary bottleneck, was effectively stabilized, validating OCF as an effective production control strategy. At the same time, the WPW revealed the absence of a structured planning methodology in the later phases, which initially were not considered to have potential bottlenecks. Unlike lagging indicators that reveal performance losses only after they occur, the WPW exposes planning fallacies in real time, allowing management to intervene and take corrective actions. In each planning cycle, the WPW can support managers in deciding whether to release additional work packages, even when constraint removal has been successfully completed, by signaling when postponing new starts is necessary to stabilize flow. Thus, the WPW functioned as a leading indicator, visualizing system overload as it began to form and prompting correction actions to improve the planning process.

From a system dynamics perspective, the WPW highlights two interacting feedback loops (Figure 8). On the one side, a reinforcing loop drives the persistence of the WPW: as more unfinished work is carried forward, WIP grows, CT increases, and flow reliability declines, reinforcing the overload in subsequent cycles. This explains why in some projects unfinished

work repeatedly rolls forward, inflating the WIP and sustaining the reinforcing loop. On the other side, a balancing loop, grounded in production management principles (e.g. the principles of the OCF strategy), provides the counterforce: strategic planning, constraint removal, restructuring resources, and controlling project starts, can collectively suppress the reinforcing wave and reestablish flow stability.

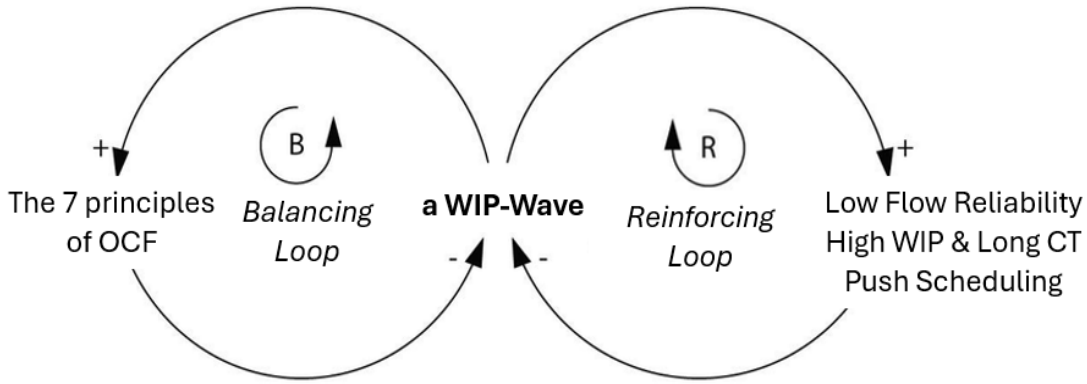

Figure 8: Balancing and reinforcing loops for the WIP-Push-Wave

The WPW sheds light on the role of cognitive biases in project planning. Optimism bias and the planning fallacy (Kahneman and Tversky 1979) describe the tendency of planners to overestimate future performance and underestimate risk. In construction planning, this bias does not appear as a single misjudgment but as a recurring pattern: cycle after cycle, project teams assume that all unfinished tasks can be absorbed in the next plan, despite clear evidence of limited capacity. This pattern is consistent with documented behavioral biases in project planning (Ansar and Flyvbjerg 2022; Flyvbjerg et al. 2018). The WPW provides an empirical and quantitative signal of this repeated overcommitment, demonstrating how psychological tendencies translate into systemic planning behavior. By exposing this recurring fallacy, the WPW helps managers recognize when they are locked in a self-reinforcing loop of over-optimism and encourages corrective actions.

The study focused on planning dynamics that generate the WPW phenomenon. However, external factors, behavioural decision mechanisms, and quantitative validation of WPW direct and indirect effects on performance requires additional analysed and remain areas for future research. This study is based on a single portfolio case study within a semiconductor construction program at one site; therefore, further research is required to examine the applicability of the WPW indicator and to validate it across different project environments and additional portfolios. Future research should also examine the relationship between WPW and PPC. While PPC measures the reliability of weekly commitments at the task level, WPW captures the systemic outcome of those commitments at the production-system level. An open question is whether WPW can be interpreted as an aggregate effect of low PPC, or whether it captures additional dimensions of planning failure that PPC alone cannot reveal. Investigating this relationship could clarify how leading indicators interact across different levels of planning and control.

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