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REDUCTION OF FLOOR CYCLE TIME VARIABILITY IN HIGH-RISE BUILDING CONSTRUCTION

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ABSTRACT

High-rise building construction projects, characterized by their inherent complexity and susceptibility to unpredictable variations such as complex logistics, weather, and resource availability, often face challenges in maintaining schedule reliability. Despite the potential for optimization due to the repetitive nature of high-rise structures, traditional planning methods struggle to address the cascading effects of variability, resulting in long cycle times for completed floors and frequent shifts in estimated completion dates. This paper presents the outcomes of implementing a Last Planner System (LPS)-based strategy for the structural frame of two high-rise buildings. Key performance metrics such as cycle time, production rates, and labor productivity were chosen to evaluate the impact. The findings demonstrate that detailed operational planning and interventions to support continuous improvement reduce the floor cycle time and its variability. Furthermore, the results offer tangible evidence of actual performance, providing practitioners with the necessary data to create more realistic master plans. This approach enhances the operational efficiency of high-rise construction projects and contributes to the broader understanding of effective strategies for managing schedule variability.

KEYWORDS

Phase scheduling, flow, variability, continuous improvement, standardization.

INTRODUCTION

The Last Planner System (LPS) is widely recognized for its effectiveness in improving production planning and control, steering projects toward their goals (Ballard & Tommelein, 2021). Despite decades of lean research and industry practice, many construction firms still rely on traditional methods like Gantt Charts and a transformational view of construction (Bølviken & Koskela, 2016). Previous research has investigated high-rise building construction, with a particular focus on the production planning of control for interior finishing work (Sacks et al., 2005), façade installation (Friblick et al., 2009), and formwork technologies (Abou Ibrahim & Hamzeh, 2015). Moreover, some studies in high-rise construction have explored the effect of learning curves on specific activities such as interior wall installation (Lee et al., 2015), formwork installation, and rebar fabrication and installation (Nguyen & Nguyen, 2013). Despite these efforts, there appears to be a notable gap in prior research concerning the

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assessment of floor cycle time performance for structural frames in high-rise construction and its association with overall project performance, including floor-level production rates and labor productivity (Murguia et al., 2022). Understanding the relationship between cycle times and project performance serves as evidence to advance the adoption of lean construction techniques in the sector further.

High-rise building structures face challenges such as resource availability, supply chain issues, complex logistics, and weather, leading to unpredictable cycle times and significant delays. To address these challenges, an LPS-based implementation strategy involving daily work planning, design of operations, and continuous improvement was implemented in this research during the structural phase of high-rise building construction. Two high-rise buildings in Mexico City using in-situ reinforced concrete structures with post-tensioned slabs were investigated as case studies. The structural frame contractor confronted the challenge of accelerating concrete structure delivery due to unforeseen delays, presenting an opportunity to introduce optimization tools to minimize cycle times and bridge the gap between plans and actuals. The paper details the specific tools implemented in the case studies, such as collaborative operation analysis, crew balance charts, and time-motion studies. The primary objectives were to manage variability in floor cycle time and quantify project performance metrics, including floor-level production rates and labor productivity. The results address current gaps in project planning and control for the structural frame in high-rise building construction. Furthermore, the findings contribute to planning more precise (and realistic) master schedules for clients, cost consultants, and contractors in agreeing upon project milestones. This research seeks to provide evidence of performance improvement and illustrate the possibilities when production planning and control are coupled with meaningful project control metrics.

RESEARCH BACKGROUND

Cycle time variability is prevalent in construction projects and necessitates effective management. Reducing and coping with variability is a key concept in lean construction (Thomas, 2002). The LPS was developed to protect construction operations from upstream flow variability (Ballard & Tommelein, 2021). However, variations in production systems can be reduced but never eliminated. Therefore, an LPS-based implementation strategy, including detailed work planning and design of operations, are required to absorb those variations and shield-protect targets. In addition, effective performance evaluation metrics are needed to assess the effectiveness of interventions.

CYCLE TIME AND VARIABILITY

Cycle time is defined as the cumulative duration of activities minus overlaps between activities plus the sum of waiting times (i.e. work discontinuities). Consequently, cycle times can be reduced by reducing waiting times and activity durations and increasing overlapping activities (Ballard, 2001). Gabai & Sacks (2020) provided strong evidence of cycle time reduction of up to 48% by implementing a lean-based method called "optimized installation flow" in industrial infrastructure installation in the semiconductor industry. In structural frame construction, the floor cycle time is the time elapsed between installing the first vertical element on a floor (start date) and the last slab concrete pour on that floor (finish date).

DAILY WORK PLANNING AND DESIGN OF OPERATIONS

A wealth of evidence, both in research and practice, supports the implementation of weekly work planning within the LPS. However, one of the least implemented components of the LPS is the design of operations at the daily planning level (Ballard & Tommelein, 2021). The design of operations entails collaborative planning among Last Planners (foremen or front-line supervisors) and craft workers responsible for executing the tasks. Operations encompass the steps to be carried out by one or multiple workers, specifying the steps, durations, sequence, individuals responsible for each step, and the pathways for workers, equipment, and materials (Ballard & Tommelein, 2021). Previous research has investigated productivity enhancement through detailed production planning, involving eliminating non-contributory work and increasing the Percent Plan Complete (PPC) (Ghio, 1997). The findings underscored the need for daily work planning to effectively manage change orders and devise efficient task completion strategies without escalating the workforce size. However, there is still insufficient evidence of the relationship between daily work planning and project performance metrics.

PROJECT PERFORMANCE METRICS

The expanding body of literature reveals a growing understanding of the relationship between production planning and control within the LPS, and its impact on project performance. Pérez et al. (2022) delved into key LPS metrics to evaluate project performance in high-rise buildings. Analyzing a dataset of 71 projects in Chile, they correlated production planning and control metrics, namely Percent Plan Complete (PPC) and constraint removal time (CRT), with output metrics such as the schedule performance index (SPI) at the planned completion point. The results indicated moderate correlations (between 0.3 and 0.4) between PPC, CRT, and SPI. Similarly, Liu & Ballard (2009) demonstrated the need for daily planning to enhance workflow reliability and labor productivity. Analyzing data from 592 working days, they found moderate associations between labor productivity and PPC with commitment plans and favorable weather conditions (correlations between 0.34 and 0.42). Arumugam & Varghese (2014) proposed a method to characterize flow in the reinforced concrete structure of high-rise apartment buildings, noting a floor cycle time of 6 to 8 days. However, as the floor area per level was not reported, benchmarking a floor-level production rate was not feasible. In contrast, Veran-Leigh et al. (2022) provided benchmark values for production rates of structural works of 63 m²/day and 73 m²/day but did not correlate PPC metrics with performance values.

RESEARCH METHOD

This research selected the case study approach to investigate the phenomenon (i.e., the case) in depth and within its context (Yin, 2014). Several sources of data were collected to achieve the research objectives: project documents (contractual programs, daily plans, design of operations), quantitative data (concrete pours, crew size, number of worker-hours), and qualitative data (on-site research observations) during the structural frame construction. Data were screened to ensure quality and analyzed using statistical tools. Based on Murguia et al. (2023), the following performance metrics were established: cycle time (days), production rate (m^2/day), and labor productivity (m^2/worker-hour). These metrics align with the research aim, which is to provide evidence-based project performance due to the implementation of daily work planning and continuous improvement strategies.

CASE STUDY DESCRIPTION

Project U, a 60-story residential development in downtown Mexico City, features 18 basement levels, a Total Gross Floor Area (TGFA) of 48,745 m² and a total height of 207 m. The typical floor has 847 m² of Gross Floor Area (GFA). Figure 1 shows the typical floor plan. The structural frame is a reinforced concrete structure with post-tensioned slabs and an average rebar density of 88 kg/m². Construction commenced in May 2021, and a single tower crane was part of the construction strategy. Project P, a 31-story luxury hotel project in a high-end residential neighborhood with a total height of 106 m, boasts a TGFA of 27,432 m², with floors averaging 945 m². Each floor was divided into two slab pouring events to accelerate the schedule (Figure 1 shows the typical floor plan with the division considered). Unlike Project U, the main structure had an average rebar density of 107 kg/m², reflecting higher structural safety standards demanded by the client. For both projects, the typical activities within the floor cycle included setting out, vertical rebar (columns and shear walls), vertical formwork, concrete pour of vertical elements, beam formwork, beam rebar, slab falsework and formwork, slab rebar and slab pours.

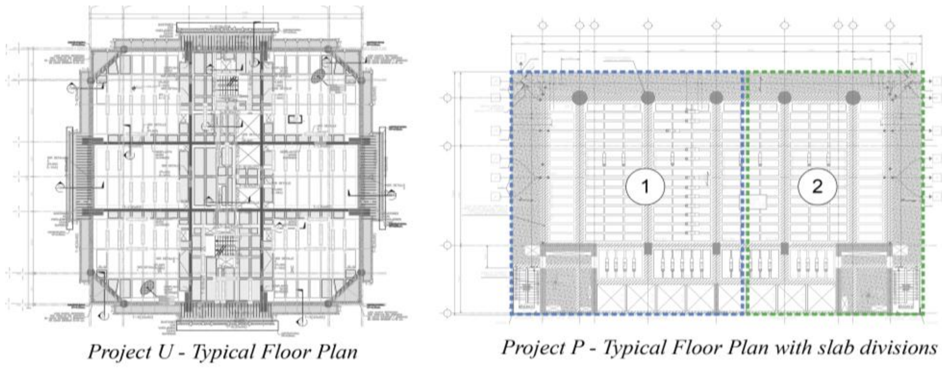


Figure 1: Project U and Project P's typical floor plans

LPS-Based Implementation Strategy

Both projects implemented a lean-based approach led by the contractor's top management and an external lean consultant. Field engineers and crew leaders actively led daily work planning sessions, conducted collaborative operation analyses, and monitored crew balance charts. Figure 2 illustrates the key steps of the LPS-based implementation strategy.

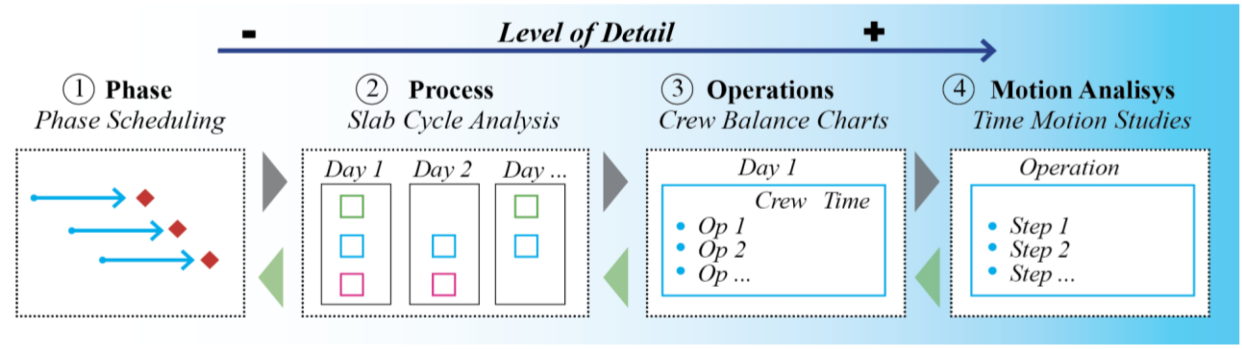


Figure 2: LPS-based implementation strategy

1. *Develop a phase schedule*: A collaborative schedule was developed by field engineers and project managers, incorporating milestones agreed upon with the developer. This step provided a robust framework for sequencing and monitoring progress.
2. *Slab cycle analysis – Daily operations by crew*: Through workshops with crew leaders, a collaborative approach was used to define the entire slab cycle for carpenters, steel fixers and concrete gangs. This ensured buy-in and alignment from all participants.
3. *Implementation and evaluation - Crew Balance Charts:* Operations listed on the corresponding day of the slab cycle analysis were handed to each crew using Crew Balance Charts and evaluated at the end of the day.
4. *Time-Motion Studies*: All the operations in the slab cycle, starting with the most repetitive, were analyzed using Time-Motion Studies. This allowed for a better understanding of all the steps involved in the operations and included suggestions from workers and field engineers.

RESULTS

The strategy was implemented from level 25 onwards on Project U and after level 3 on Project P, leading to different outcomes. In Project U, the structural frame reached the 25th floor with delays exceeding the contractual timeline. Further complicating matters, Project U experienced highly variable slab cycle times ranging from a swift 10 days to a staggering 54 days, primarily due to unforeseen disruptions caused by overlooked activities in the program, such as rebar bending or tower crane availability. On the other hand, the developer in Project P requested faster delivery times. However, Project P faced unique challenges, including the developer's control over the tower crane, which limited material availability for the contractor, especially rebar and falsework movement. Furthermore, Project P's spatial constraints needed off-site rebar cutting and bending, impacting additional processes such as pre-ordering and increasing inventory management efforts owing to large batches for reduced shipping costs. Moreover, the implementation strategy encountered significant organizational challenges, such as limited engagement from both crew and engineers, undefined roles, overlapping responsibilities, and communication problems. These issues required resolution before the implementation of the strategy, underscoring the critical role of robust on-site management in ensuring planning at the operational level and project success.

(1) PHASE SCHEDULING

A collaborative planning session was conducted in line with pre-established milestones agreed upon with the owner's project managers, superintendents, and field engineers. This session brought together structural engineers with the construction team to thoroughly understand project constraints and determine the feasible number of slab partitions considering the structural design. In Project P, this analysis concluded that two pouring events were possible, while Project U could only accommodate one. This crucial definition directly informs the overall schedule and subsequent strategic decisions.

Additionally, these sessions established the general sequence and order of activities based on the specific site context. Factors considered included tower crane placement, personnel access, and material supply. This collaborative approach ensured optimal planning tailored to the unique conditions of each project.

(2) SLAB CYCLE ANALYSIS: DAILY OPERATIONS PER CREW

At the outset of the implementation strategy, superintendents, field engineers, and crew leaders collaborated to develop detailed slab construction cycles for both projects. Project P achieved a 9-day cycle, while Project U required a 10-day cycle. These cycles outlined daily operations and responsibilities for carpenters, steel fixers, and concrete crews, highlighting critical interactions and potential constraints faced by each team (e.g., crane availability, dependencies on previous tasks, material availability, and post-tensioning requirements).

These slab cycles served as a starting point and were revised throughout the project lifecycle. Bi-weekly on-site reviews, led by the superintendent and lean consultant, incorporated lessons learned from time-motion studies and addressed execution challenges, such as overlapping activities and material handling issues.

Marked-up floor plans served as crucial visual aids in this process. Crews used these plans to map out the daily operation sequence, specifying required work hours, work quantities (kg, m2, m3), and specific locations for each task. Figure 3 exemplifies this concept for Day #3 of the slab cycle in Project U, focusing on rebar installation. It illustrates the operational sequence, labor resource allocation, and a color-coded layout to facilitate spatial coordination. This detailed planning process enhanced crew coordination and minimized unforeseen disruptions during construction.

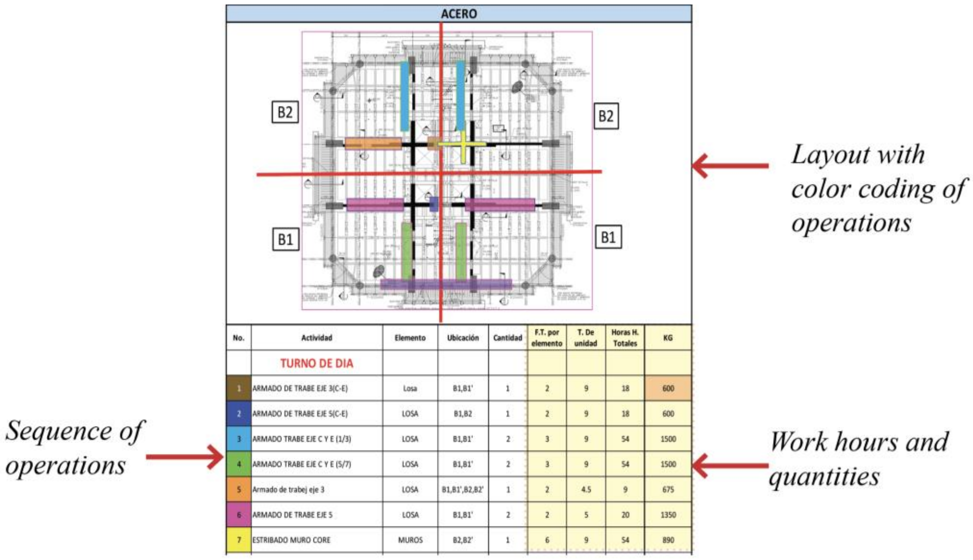


Figure 3: Visual aid example for Daily Work Plan (Project U)

(3) Crew Balance Charts

At the end of each workday, and based on the corresponding slab cycle plan, field engineers and crew leaders convened to develop Crew Balance Charts (CBC) to assign activities to carpenters, steel fixers and concrete finishers. These CBCs were handed to each crew member, detailing the operations expected for the following day, specifying the allocated worker-hours, time of day, crew identification, material quantities, and its location within the slab (Figure 4). During these on-site meetings, field engineers evaluated the operations performed during the day and any challenges encountered. Based on this evaluation, the team adjusted the CBC for the following day, incorporating mitigation plans when necessary.

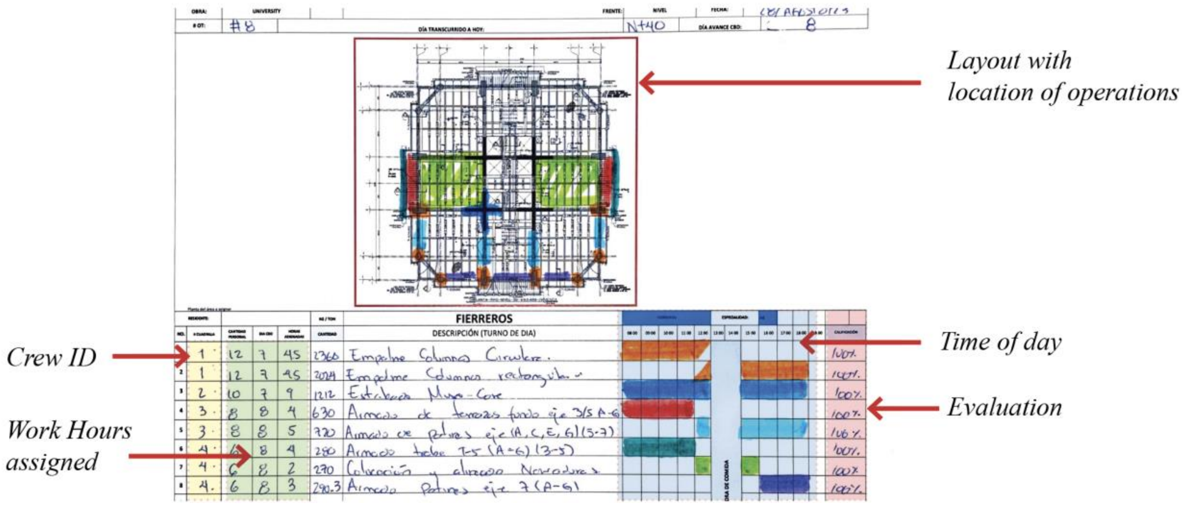
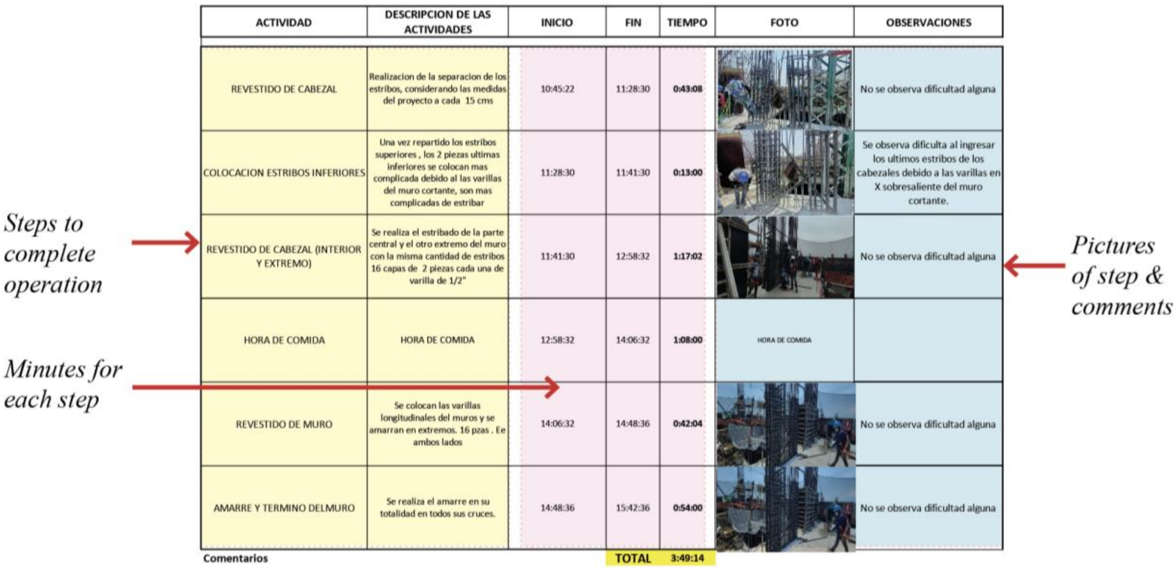


Figure 4: Crew Balance Chart for steel fixers

(4) Time-Motion Studies

To further refine the process and to validate the time considered in the slab cycle, time-motion studies were conducted by the lean consultants on most operations, starting with repetitive operations constituting up to 80% of the slab cycle, such as standard columns, shear walls and main beams. An illustration of one such study is depicted in Figure 5, focusing on rebar installation within a shear wall. The study outlined all necessary steps for completing the shear wall and the allocated time for each step, accompanied by a concise description, visual aids, and observations regarding potential improvements.

This approach fostered a collaborative environment by actively incorporating crew members and field engineers to suggest improvements for individual steps within each operation, ultimately enhancing overall slab construction performance. These studies not only validated execution times for future slab cycles but also highlighted opportunities for improvement, prompting targeted problem-solving efforts. Additionally, they served as valuable resources for training new crews on-site and standardizing procedures across all existing teams.



ACTIVIDAD	DESCRIPCION DE LAS ACTIVIDADES	INICIO	FIN	TIEMPO	FOTO	OBSERVACIONES
REVESTIDO DE CABEZAL	Realizacion de la separacion de los estribos, considerando las medidas del proyecto a cada 15 cms	10:45:22	11:28:30	0:43:08		No se observa dificultad alguna
COLOCACION ESTRIBOS INFERIORES	Una vez repartido los estribos superiores , los 2 piezas ultimas inferiores se colocan mas complicada debido al las varillas del muro cortante, son mas complicadas de estribar	11:28:30	11:41:30	0:13:00		Se observa dificulta al ingresar los ultimos estribos de los cabezales debido a las varillas en X sobresaliente del muro cortante.
REVESTIDO DE CABEZAL (INTERIOR Y EXTREMO)	Se realiza el estribado de la parte central y el otro extremo del muro con la misma cantidad de estribos 16 capas de 2 piezas cada una de varilla de 1/2"	11:41:30	12:58:32	1:17:02		No se observa dificultad alguna
HORA DE COMIDA	HORA DE COMIDA	12:58:32	14:06:32	1:08:00	HORA DE COMIDA	
REVESTIDO DE MURO	Se colocan las varillas longitudinales del muros y se amarran en extremos. 16 pzas . Ee ambos lados	14:06:32	14:48:36	0:42:04		No se observa dificultad alguna
AMARRE Y TERMINO DELMURO	Se realiza el amarre en su totalidad en todos sus cruces.	14:48:36	15:42:36	0:54:00		No se observa dificultad alguna
Comentarios			TOTAL	3:49:14		

Figure 5: Time-motion study example of rebar installation in shear walls

PROJECT PERFORMANCE

To visualize project performance, the master-level flowlines, as described in Murguia et al. (2023), were used to compare plans and actuals for both projects. Furthermore, production rates and labor productivity were estimated from the labor and concrete pour data. The flowlines in Figures 7a and 7b show that both projects missed the contractual completion dates for the structural frame. However, the strategy described in this paper was implemented from the 25th floor onwards on Project U. As shown in Figure 7a, this led to a noticeable acceleration in the cycle time, represented by the steeper slope of the actual line after that level. Had this strategy not been implemented, the project would have likely overrun the contractual deadline even further. The review of the actual performance results showed that the contractual dates for Project P were unrealistic because planners during the tender stage considered weekends or holidays within the contractual cycle times. These observations were evident in the unreasonably short timeframes, such as 7 days for completing 945 m^2 of work, creating a pace of 135 m^2/day, not very common in the industry for in-situ reinforced concrete frames with a single crane.

The boxplots in Figure 8 summarize the cycle time data. During the first stage of Project U (Floors 7- 25), the minimum cycle time was 10 days, whilst the maximum was 24 days (some outliers up to 54 are outside the boxplot). The median was 15 days. Additionally, the first and third quartiles were estimated at 12 and 17 days, respectively, suggesting an interquartile range of 5 days. During the second stage of Project U (Floors 26-50), the minimum cycle time was recorded at 9 days, whilst the maximum was 14 days. The median cycle time was 11 days. Furthermore, the first and third quartiles were estimated at 10 and 12 days, respectively, suggesting an interquartile range of 2 days. Therefore, substantially less variability was achieved. Finally, the minimum cycle time for Project P was recorded at 9 days, whilst the maximum was 19 days. The median cycle time was 14.5 days. Moreover, the first and third quartiles were estimated at 13 and 16 days, respectively, suggesting an interquartile range of 3 days, suggesting less variability.

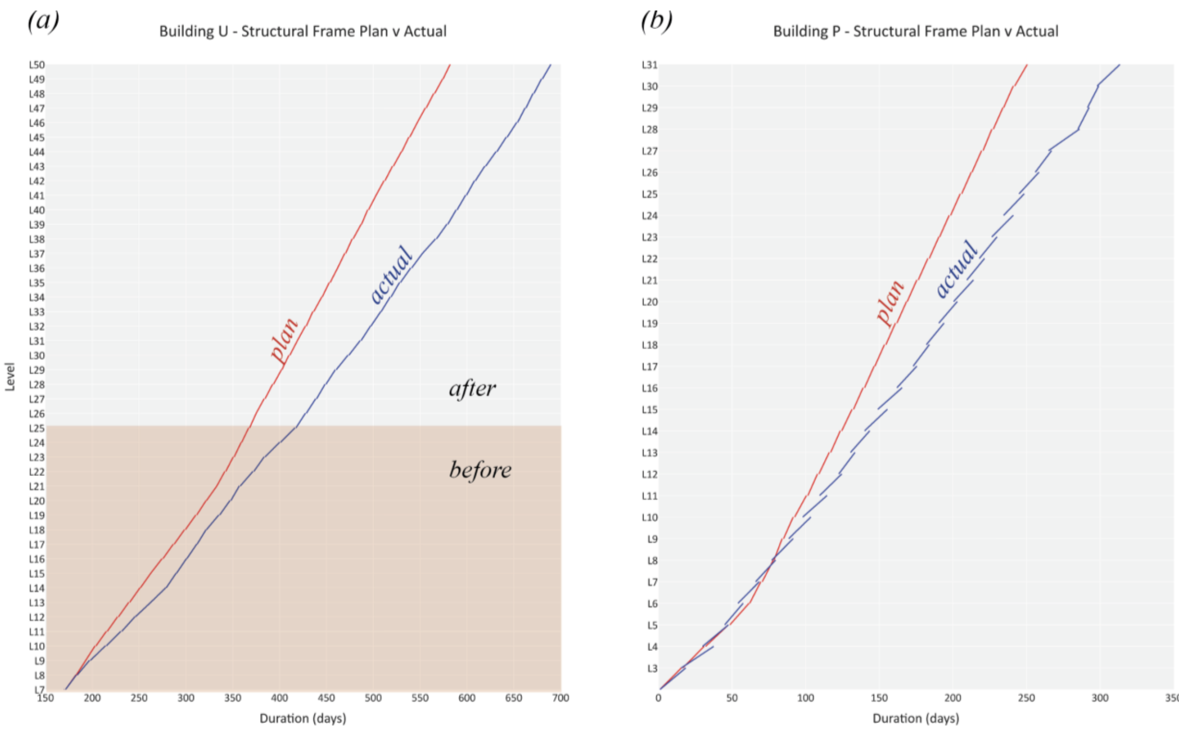


Figure 7a and Figure 7b: Flowlines (plan v actual) for Projects U and P

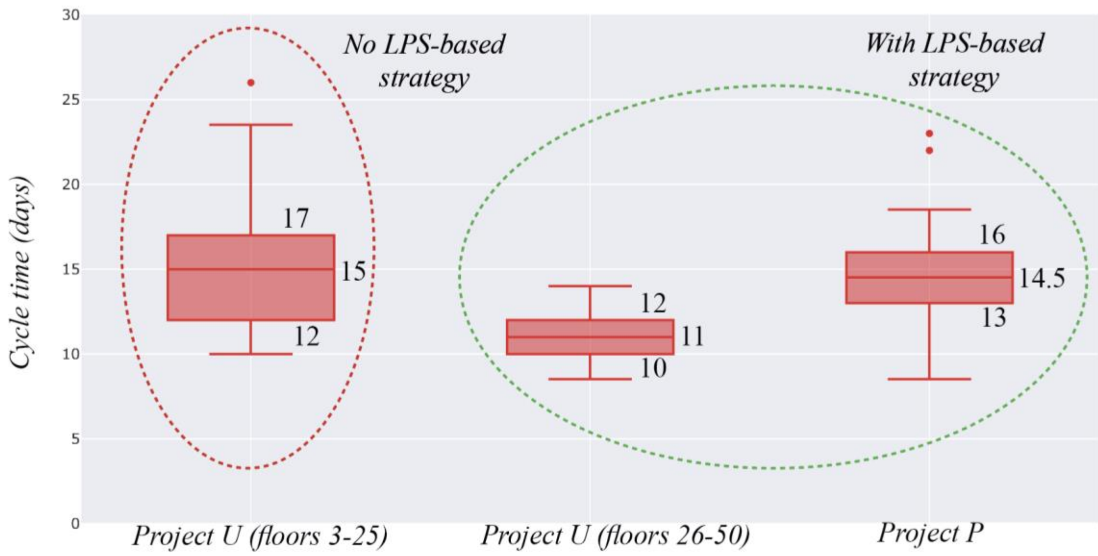


Figure 8: Cycle Time Boxplots for Projects P and U

TIME COMPRESSION AND WORKFORCE REDUCTION

Both projects experienced a significant acceleration in construction speed due to increased production rates, measured in square meters of GFA delivered per day. Notably, this was achieved while simultaneously reducing the number of workers required to complete each floor. For Project U (see Figure 9), the production rate before implementing the described LPS-based strategy (floors 7-25) was an average of 53 m²/day. In comparison, after implementing the LPS-based strategy (floors 25+), the average production soared to 79 m²/day, representing a **49% increase**, whilst **the number of workers had a reduction of 30%**. Overall, comparing phase 1 (levels 7-25) to phase 2 (levels 26-49), productivity increased from 3.5 m^2/100 worker-hours to 13.1 m^2/100 worker-hours, an astounding **274% increase**. In the case of Project P (see Figure 10), the production rate started at 67 m²/day and finished at 145 m²/day, marking a remarkable **116% increase**. In terms of the number of workers, there was a **29% reduction**.

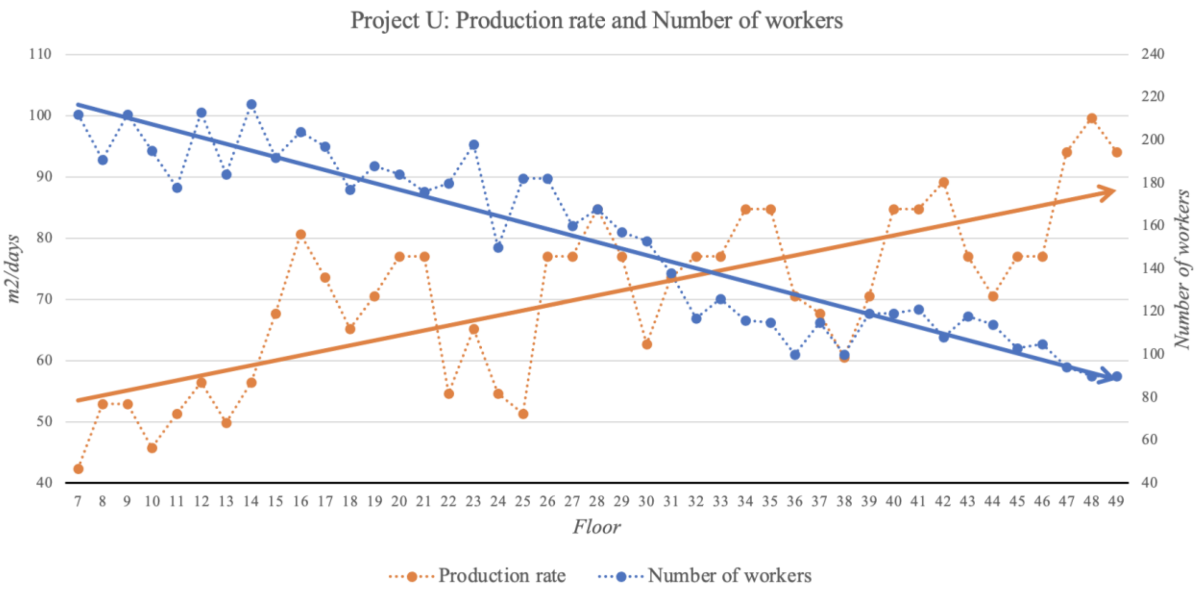


Figure 9: Productivity Metrics Project U

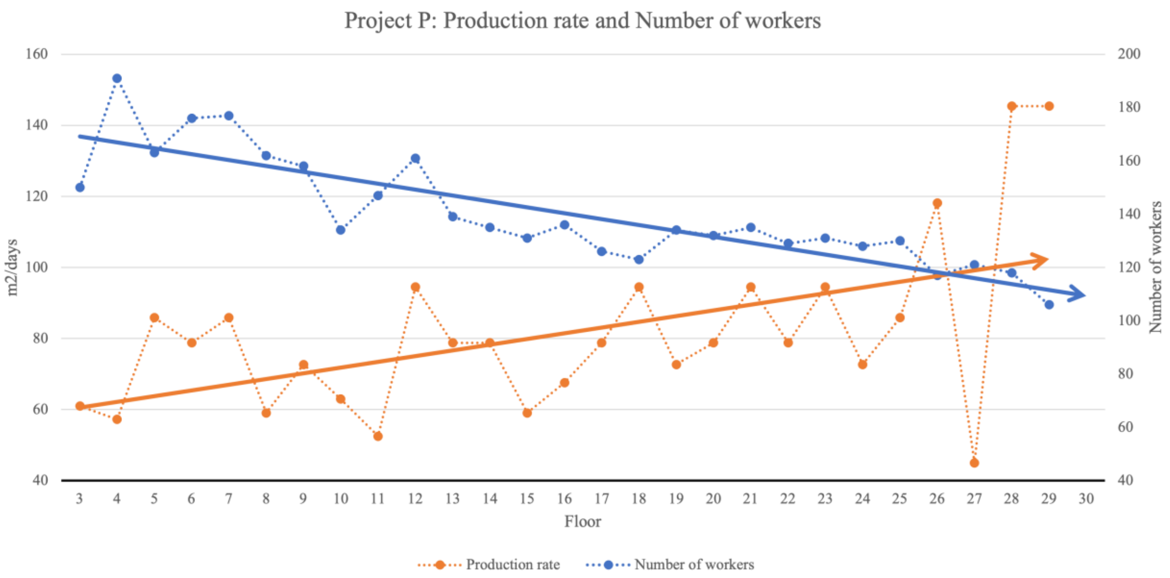


Figure 10: Productivity Metrics Project P

BEYOND PRODUCTIVITY: ADDITIONAL OUTCOMES

Building upon the productivity gains, both projects experienced **significant reductions in worker turnover.** Before the LPS-based implementation strategy, both projects faced substantial monthly worker rotation, averaging *41% for Project U and 43% for Project P*. These figures decreased to 18% and 24% on average for Projects U and P, respectively. The turnover decrease proved crucial for successfully implementing the LPS-based strategy by minimizing knowledge loss and the need for constant training of new workers. While a baseline level of worker turnover persisted, around 20% on average, on-site workers reported improved overall satisfaction. The initiatives described in this paper, including a 22% salary increase, likely contributed substantially to this positive shift in morale and commitment to continuous improvement.

DISCUSSION

UNREALISTIC CONTRACTUAL PHASE SCHEDULE

Despite operating in distinct contexts, both projects experienced significant benefits from the LPS-based strategy but did not meet the original contractual dates (Figures 7a & 7b). The contractor's planners developed these programs within the tendering team years before construction. It is worth noting that planners at the tender stage are typically unfamiliar with actual performance data or may inadequately consider the project context. Moreover, to secure contracts, a touch of optimism bias is introduced into the master plan. A data-driven, forward-thinking client would be prepared to procure projects that align more closely with actual performance. This approach to procurement would be crucial to avoiding misalignment between planned and actual timelines and, consequently, better predicting the overall duration of the structural frame.

WIN-WIN-WIN IMPACT AND FUTURE POTENTIAL

The LPS-based implementation strategy benefited all stakeholders: developers through reduced schedule variability, contractors through cost reductions, and the workforce through increased wages. Moreover, the incentive program is based on productivity gains, using CBCs and time-motion studies, effectively motivating crews and field engineers, demonstrating its potential for early adoption in future projects. Applying this strategy to subsequent trades such as façade, services, and fit-out in high-rise buildings holds immense promise. This could prevent gains in the structural phase from being negated by later trade bottlenecks, leading to overall project efficiency optimization. Further research exploring this application could pave the way for a more streamlined and cost-effective future for high-rise construction.

CONCLUSIONS

This study presented an LPS-based implementation strategy to support variability reduction of floor cycle time in the construction of high-rise building structures. The strategy included a master phase schedule, daily work planning, crew balance charts, and time and motion studies. The strategy was implemented in two live projects in Mexico City. The results showed a significant reduction in cycle time and its variability, leading to significant performance improvement for both production rate and workforce reduction. The significant gaps between plans (client's expectations) and actual (what is possible) need to be more aligned through a data-driven performance culture. This research uniquely presents performance data that can be used for benchmarking in future studies. This study has some limitations. PPC was not captured to correlate PPC performance and cycle time variability. Furthermore, the effect of learning curves was not considered in this study. Finally, future studies can examine other work packages, such as façade and interior work, along with the integration of lean and BIM.

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