

UNDERSTANDING PERFORMANCE LIMITS IN OFF-SITE STRUCTURAL FRAME CONSTRUCTION

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ABSTRACT

Off-site construction is promoted as a means of improving productivity in the construction industry. Its standardised production processes create a favourable environment for applying lean principles. However, evidence suggests it does not always result in faster construction. We investigate the reasons by analysing the superstructure work package of a 14-storey residential building in London, using installation data for 2,070 precast columns, twin-wall cores, and lattice slab components. Construction speed, measured as the production rate (m² of floor area per day), showed a significant linear relationship with installation variability. Variability arose from factories producing similar components in batches for multiple projects, delays in issuing designs to factories, and out-of-sequence deliveries to sites with limited storage capacity. Handovers between off-site and on-site activities also exhibited greater variability than purely on-site handovers. The findings suggest that, if variability were minimised, construction speed would follow an inverse U-shaped trend, with initial improvements due to workers' learning effects, followed by subsequent reductions associated with longer transportation distances for pre-manufactured components at higher levels. This study quantifies the variability-performance relationship in off-site construction and identifies the interface variability gradient between off-site and on-site handovers.

KEYWORDS

Modular and off-site construction, productivity, variability, logistics, learning.

INTRODUCTION

Off-site construction involves the factory-based production of building components for on-site assembly. Premanufactured Value (PMV) is one of the most widely used measures of off-site construction, representing the financial proportion of construction value generated through pre-manufacturing rather than on-site labour (Cast Consultancy, 2021). Many studies claim that off-site construction is one of the main methods for improving construction labour productivity (i.e. output per worker-hour), with evidence at the industry (Eastman & Sacks, 2008), project (Shahzad et al., 2015), and activity levels (Nadi, 2019). However, this is unsurprising, as off-

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site construction replaces on-site labour with factory labour, while construction labour productivity typically accounts only for on-site labour.

A critical paradox exists: while off-site construction should theoretically enable faster construction through parallel production and reduced on-site work, evidence suggests it does not always increase construction speed at the project level (Rathnayake Mudiyansele, 2024). This performance gap, between the theoretical potential of off-site construction and its realised outcomes, represents an undertheorised area in construction management research. The mechanisms constraining off-site construction performance, particularly the interaction between internal learning effects and external supply chain variability, remain largely unexamined empirically. This study examines these mechanisms through three research questions: (RQ1) How does installation variability affect construction speed in off-site construction? (RQ2) What factors drive variability in the off-site supply chain? (RQ3) How do internal (learning) and external (supply chain) factors interact to shape overall project performance?

LITERATURE REVIEW

OFF-SITE CONSTRUCTION AND LEAN CONSTRUCTION

Both off-site construction and lean construction are related to manufacturing. Off-site construction introduces manufacturing techniques into construction, while lean construction adapts lean manufacturing principles to the project environment. Scholars argue that the repetitive, factory-based nature of off-site construction provides a suitable setting for implementing lean principles (Innella et al., 2019). However, despite this compatibility, the performance of off-site construction projects remains highly sensitive to disruptions arising across both manufacturing and on-site processes. Two key lean principles that could significantly improve off-site construction speed are low variability and a pull-driven production system, with Just-in-Time (JIT) delivery as a core tactic, which are discussed in the subsequent paragraphs.

VARIABILITY IN CONSTRUCTION OPERATIONS

Variability is a fundamental concept in production systems theory. Hopp and Spearman (2011) distinguish between process variability, which refers to differences in individual activity durations, and flow variability, which refers to fluctuations in the transfer of jobs or components from one activity to another. In construction, Koskela (2000) identified variability reduction as a core lean principle, arguing that variability undermines flow reliability and necessitates buffers, which in turn increase waste. Ballard and Howell (1998) demonstrated through the Last Planner System that reducing task duration variability enhances workflow reliability. In off-site construction, Arashpour et al. (2015) found that variability in manufacturing schedules propagates to site installation, creating a "bullwhip effect" that amplifies disruptions. However, the mechanisms through which factory batching and sequencing decisions generate on-site variability remain undertheorised, particularly at the manufacturing–installation interface.

PULL-DRIVEN PRODUCTION SYSTEM

A pull-driven production system can play a vital role in synchronising factory and site operations. Just-in-Time delivery reduces the need for on-site storage, alleviating congestion and minimising the risk of component damage, thereby enabling more efficient use of resources (Arashpour et al., 2015). Beyond logistics, a pull-based approach governs production scheduling in the factory: instead of commencing production based on forecasts, manufacturing is triggered by actual site demand, reducing overproduction and work-in-progress inventory, both significant forms of waste (Innella et al., 2019).

Innella et al. (2019) argued that lean principles, particularly pull systems and JIT delivery, should govern off-site supply chains but acknowledged that implementation remains challenging due to the project-based nature of construction. Successful implementation of a pull-based approach requires improved coordination and information flow across the entire supply chain, from design to on-site assembly (Li et al., 2014). Improving supply chain integration is a critical challenge in prefabricated construction and requires further exploration.

RESEARCH METHOD

This research adopted a case study of the superstructure work package of a 14-storey residential building in London (see Figure 1) to examine factors affecting the speed of off-site construction. The building has a total floor area of approximately 19,000 m². Superstructure works were completed between April and November 2022, following a single workflow of precast column installation, falsework, precast lattice slabs, slab reinforcement, and in-situ concreting. Precast twin-wall cores were installed in parallel with column installation (see Figure 1).

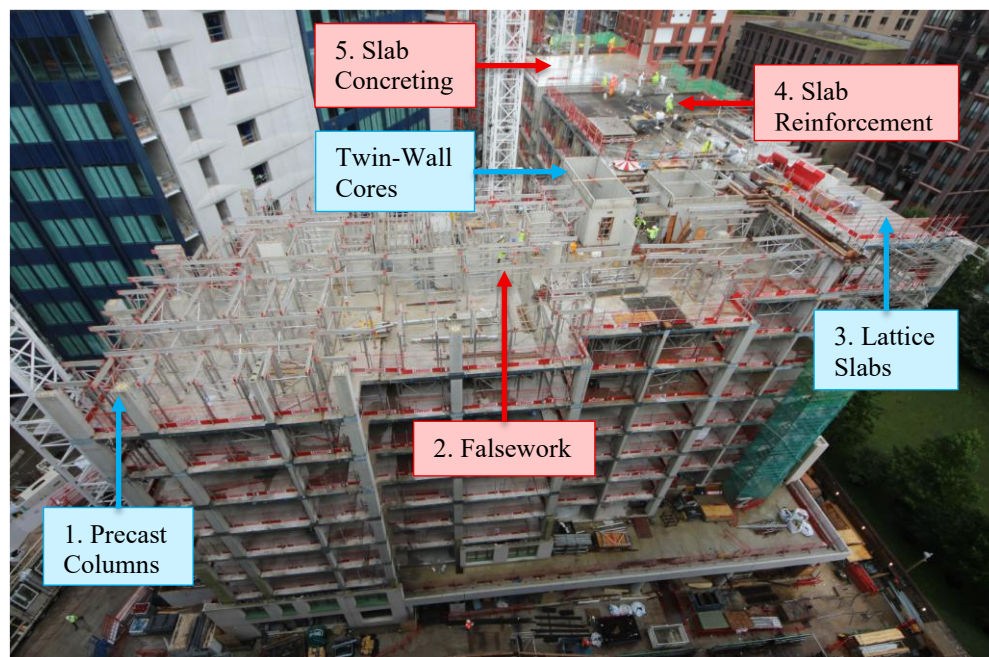


Figure 1: Selected building and its superstructure work activities (on-site activities in red boxes; off-site activities in blue boxes)

Analysis used multiple data sources to measure construction speed, installation variability, and to identify causal mechanisms. Delivery records of off-site components (precast columns, twin-wall cores, and lattice slabs) and CCTV images (captured every 15 minutes at the workface) were used to determine installation dates of off-site components. Due to limited on-site storage space, elements were typically installed on the same day they were delivered, as confirmed by CCTV records and project team members. Therefore, delivery dates were used as a proxy for installation dates; this assumption is acknowledged as a limitation.

Production rate (average floor area constructed per day) and labour productivity (average floor area per worker-hour) were calculated using BIM floor areas along with site installation and access data. The coefficient of variation ($CV = \sigma/\mu$) was used to quantify daily installation variability, while regression analysis tested its relationship with production rate. Interface durations between activities were measured from CCTV footage at 38 locations to identify limiting interfaces. Semi-structured interviews with project team members and precast factory managers supported the interpretation of quantitative findings.

According to Yin (2018), this study is a single embedded case study, and this approach can be justified in several ways: (1) the case is one of hundreds of typical concrete buildings in London, representing a common case; (2) access to a large dataset provides a revelatory opportunity to conduct an "up-close" examination of the intricate relationships between off-site manufacturing, logistics, and on-site installation variability; (3) the study has a longitudinal dimension, as the construction process across 14 floors is considered to examine changes in various factors. Finally, the analysis is embedded, as it uses multiple units of analysis, including building levels, component types, and activities. Single-case designs are appropriate for theory-building when the case provides unusual access to phenomena otherwise difficult to observe.

RESULTS

INSTALLATION PATTERN AND VARIABILITY

Figure 2 illustrates the overall progression of off-site element installation over the project duration. The total installation period was estimated at 210 days, of which 146 days (69.5%) involved active installation, while 54 days (30.5%) recorded no installation activity. The median installation rate of days with active installation was 14 pieces/day, with lower-quartile (Q1) and upper-quartile (Q3) performances of 7 and 21 pieces/day, respectively. This yields an inter-quartile range (IQR) of 14 pieces/day, equal in magnitude to the median, indicating considerable variability in daily installation rates. If days without installation are considered, the median installation drops to 9 pieces/day.

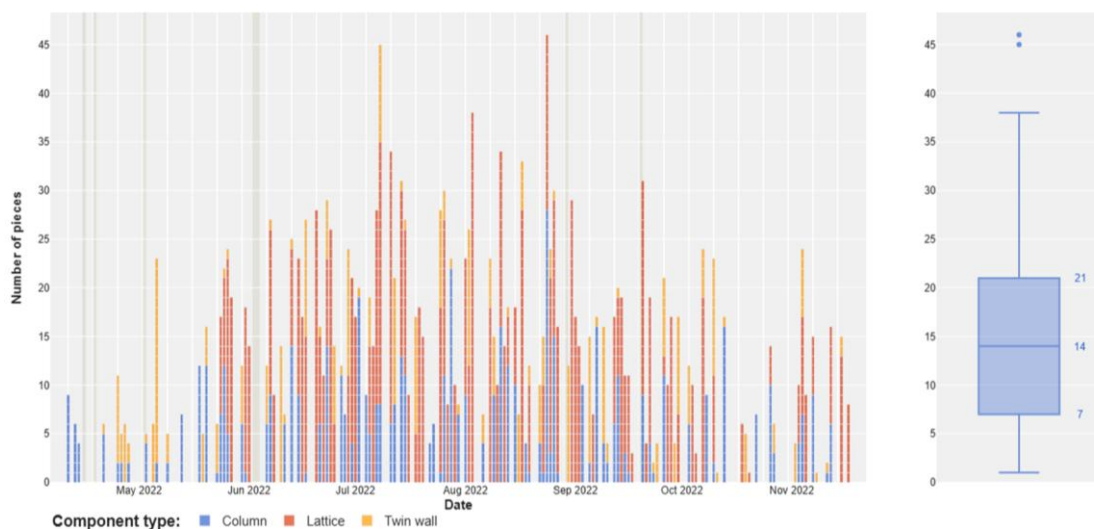


Figure 2: Overall daily piece count of off-site elements across the project duration

To further illustrate installation variability, Figure 3 presents a flowline diagram of piece installation across multiple levels. The colour scale represents the number of installed elements, with green indicating high daily output and red indicating low output; grey diagonals denote days with no installation activity. Across levels, a consistent pattern is observed: installation rates are typically lower at the start of each level (shifting towards red), increase to intermittent amber and green peaks during mid-level execution, and decline again towards the end of the cycle. The reduced output at the beginning of each level reflects the initial installation of fewer precast columns than lattice plank units. Towards the end of the cycle, installation activity overlaps with the subsequent level. As a result, daily output reflects the combined effect of completing lattice plank installation at the current level while initiating column installation at the next level, with production split across two work fronts, leading to an apparent reduction in

pieces installed per level per day. Consequently, installation variability emerges as an inherent characteristic of the system, driven by both product design and production system configuration.

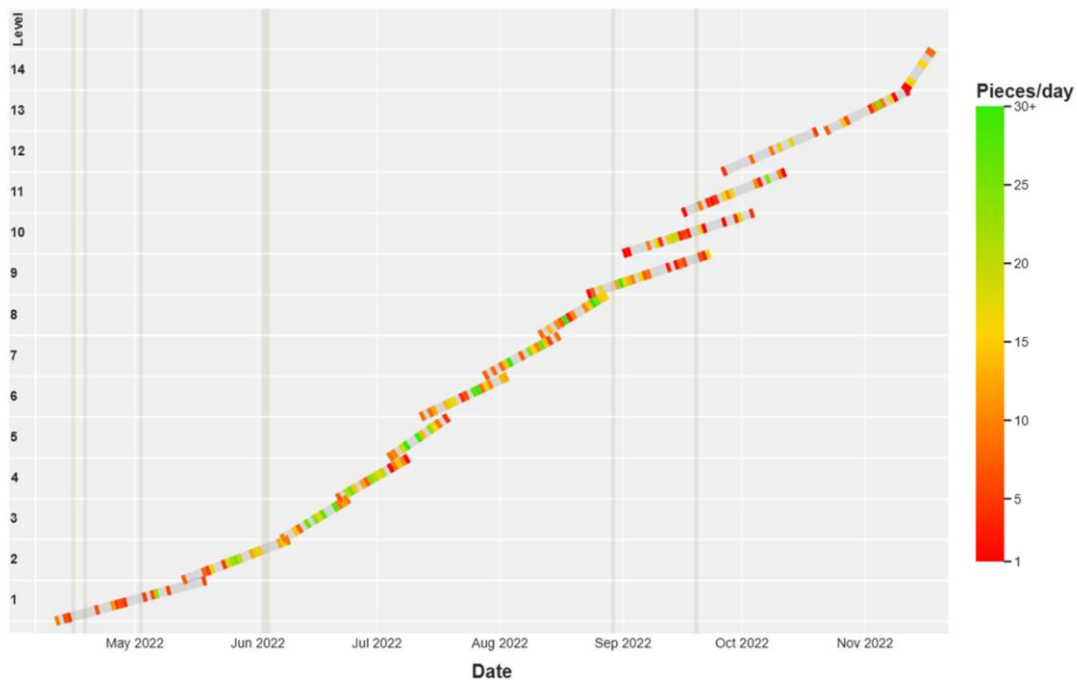


Figure 3: Off-site elements installation flowlines

To visualise performance variability by level, Figure 4 shows the distributions of daily installed off-site elements for each level, including days without installation (grey in Figure 3). The best median and Q3 performance are presented in Level 4 with 13 and 20 pieces/day, respectively. Notably, the Q1 and median for levels 1 and 12 are zero, suggesting that there are more days with no installation within the cycle. High variability is commonly cited as a characteristic of poor production flow (Hopp & Spearman, 2011).

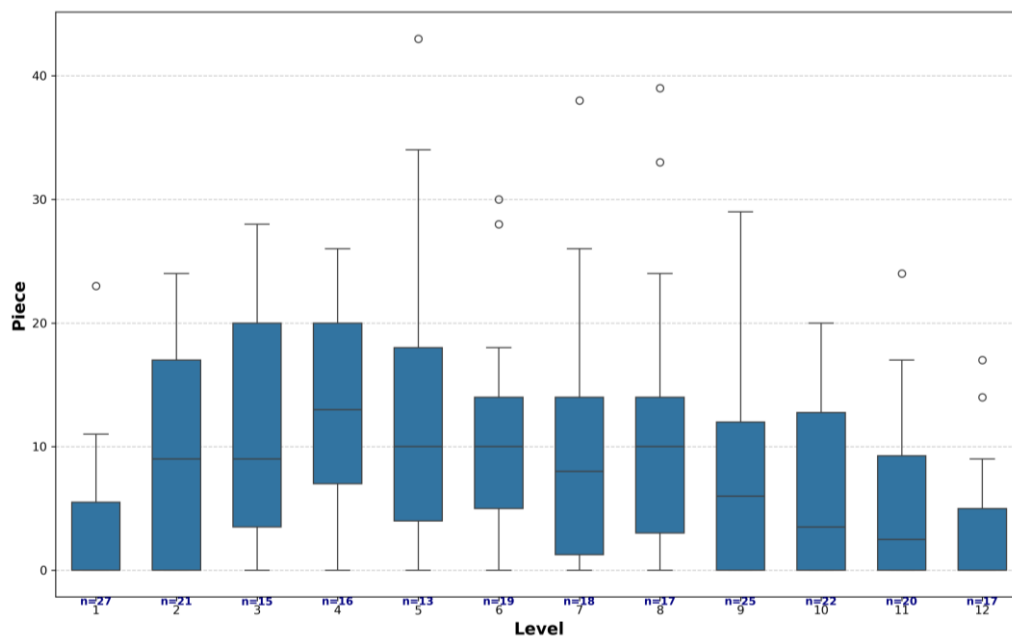


Figure 4: Distribution of daily installed off-site elements across building levels

QUANTIFYING VARIABILITY

To quantify the variability in Figure 4, two metrics were calculated: the coefficient of variation and the proportion of days without installation. The distribution of these metrics is presented in Figure 5. The average coefficient of variation and the proportion of days without installation (i.e., idle percentage) are estimated at 1.08 and 32%, respectively. The two metrics showed a very high linear correlation ($r = 0.96$; see Figure 7), indicating a strong association between levels with high day-to-day variability in installation quantities and levels with a large number of days without installation. Days without installation can be considered a consequence of high variability, whereas the coefficient of variation directly measures variability.

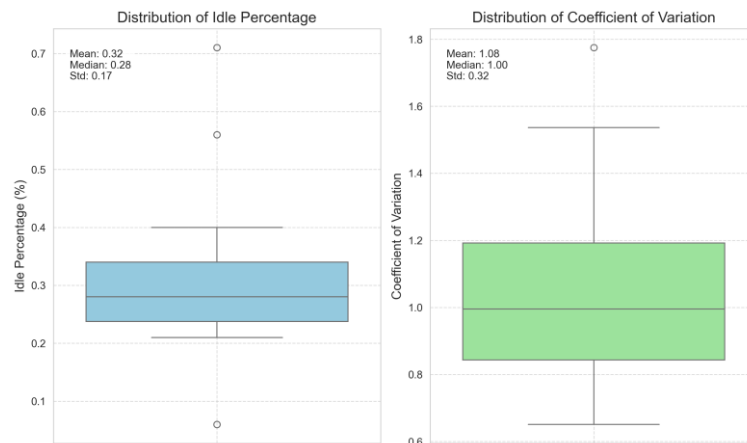


Figure 5: Distribution of idle percentage and CV

LEARNING EFFECT AND CONSTRUCTION SPEED

The primary objective of adopting new technologies such as off-site construction is to improve construction speed (i.e., production rate). However, construction speed is not static during a project and typically increases with repetition, a phenomenon known as the learning effect (Thomas et al., 1986). Learning curves are usually developed with respect to labour productivity (i.e., output per worker-hour), as improvements are mainly attributed to human factors such as increased worker familiarisation, improved coordination of equipment and crews, and the development of more efficient working methods (Thomas et al., 1986). Figure 5 shows the variation in production rate alongside a learning curve developed for the same building, expressed as the reciprocal of cumulative average labour productivity. Learning curves are commonly plotted as cumulative averages to highlight underlying trends.

According to Figure 6, the learning curve exhibits a U-shaped pattern, indicating that labour productivity increased from Levels 2 to 8 and subsequently declined. This pattern is commonly observed in construction projects and can be explained by several factors. Higher building levels require more worker-hours due to longer crane travel times and longer worker access times, particularly on off-site projects with a high number of prefabricated components. Additionally, roof levels often feature distinct structural designs to accommodate mechanical systems, increased ceiling heights, and other architectural requirements (Rathnayake et al., 2024).

Another contributing factor to reduced labour productivity at higher levels is the failure to proportionally reduce the number of workers as floor plate sizes decrease. According to project personnel, workers are often retained on-site even when workloads decrease, to prevent them from moving to other companies (Rathnayake et al., 2024). The production rate generally follows a similar increasing-decreasing trend. However, unlike the learning curve, the maximum production rate was achieved at Level 4, although Level 8 also shows a local

maximum. Critically, this divergence between production rate (peaking at Level 4) and labour productivity (peaking at Level 8) suggests that external supply chain disruptions suppressed production rate before internal factors would have naturally limited it. Interview data corroborate this: factory delays and out-of-sequence deliveries were concentrated in Levels 5-7, corresponding to the period when production rate would have continued rising absent such disruptions.

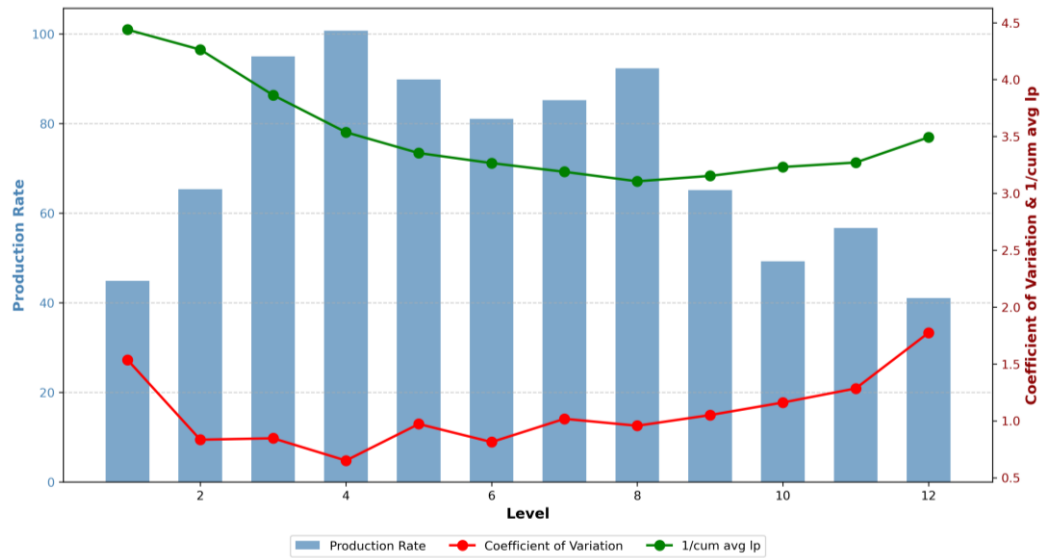


Figure 6: Variation of production rate compared to the learning curve and CV

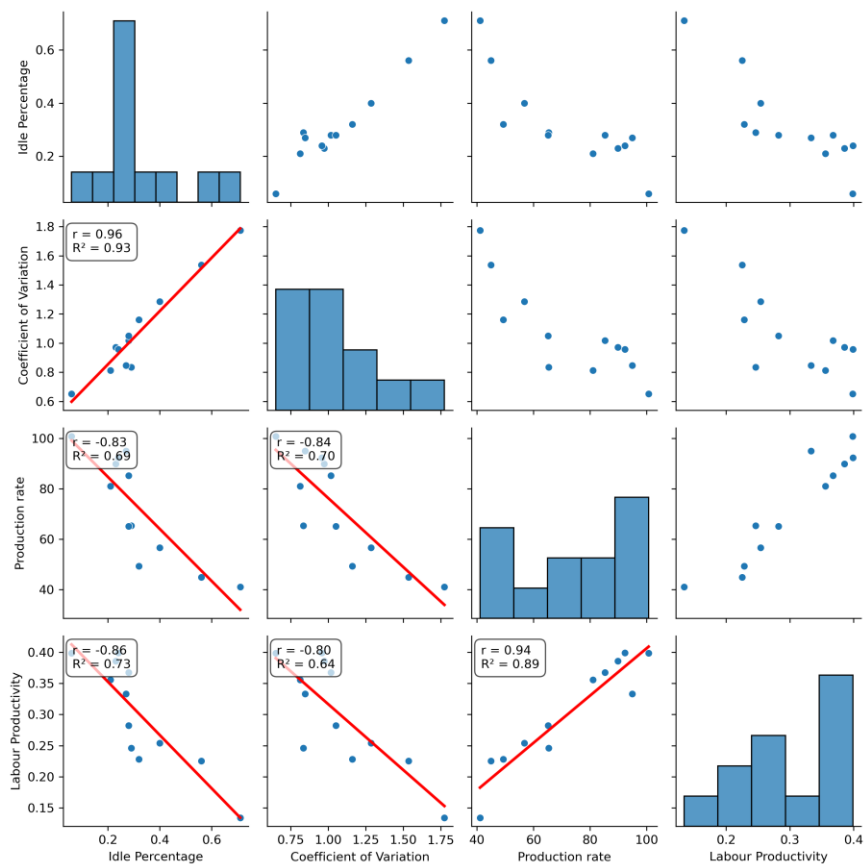


Figure 7: Relationships between the idle percentage, CV, production rate, and labour productivity

Figure 7 summarises the relationships among the variables under examination. Strong associations are observed, as reflected by the Spearman correlation coefficient (r) and the coefficient of determination (R^2). Both production rate and labour productivity exhibit negative associations with process variability, measured by the CV, as well as with idle percentage (i.e., proportion of days without installation). The strongest association is observed between the CV and idle percentage ($r=0.96$), indicating a strong monotonic relationship. This suggests that idle percentage may function as a disruption-related indicator, capturing interruptions to workflow continuity that are associated with increased variability and early signs of performance degradation.

EXTERNAL FACTORS INFLUENCING VARIABILITY AND CONSTRUCTION SPEED

Figure 6 also illustrates the variation in the CV across levels. Similar to the learning curve, it follows a U-shaped pattern. This may be partially explained by the same mechanisms underlying the learning effect, as increased worker familiarity can lead to more consistent work patterns. However, unlike the learning curve, the minimum CV occurs at Level 4. Another possible reason for the U-shaped pattern of the CV might be the number of working locations in the building. The project had four locations per floor from Levels 1-9, after which this was reduced to three due to a decrease in the overall slab area. This resulted in fewer parallel working locations at any given time. On these latter levels, site cameras showed that many days were without installation due to the unavailability of work areas. Nevertheless, according to interviewees, installation variability was primarily influenced by external factors, including supply chain disruptions, site constraints, and logistical challenges. A major source of supply chain disruption was factory delays, which resulted from either late design information being issued to manufacturers or factories prioritising other projects. In addition, factories typically prioritise bulk production, which can result in components being delivered out of sequence. Due to the lack of on-site storage space, such elements often had to be returned to the factory. This shows how misaligned objectives between manufacturers and contractors create coordination failures.

In summary, for this project, the production rate can be understood as the combined outcome of internal factors, such as the learning effect, vertical transportation delays, and the number of working locations, and external factors, such as supply chain disruptions, which are captured through the CV. If external issues had not occurred, the production rate would likely have continued to increase until at least Level 8, consistent with the learning curve. Figure 5 presents a comparison of these relationships.

LOSSES AT INTERFACES

One of the key technical limitations in off-site construction is the difficulty encountered at physical interfaces (Pan et al., 2023), namely the connections between off-site–on-site or off-site–off-site elements, which represent handovers between different crews. Although handover durations would ideally be measured as finish-to-start times, it was observed that, due to the relatively large working areas, crews often started work at a location before the previous crew had finished. Therefore, start-to-start durations between successive crews were used as a measure of handover duration. In this project, start-to-start durations for the five main activities were measured from CCTV footage, and their variations are shown in Figures 8 and 9.

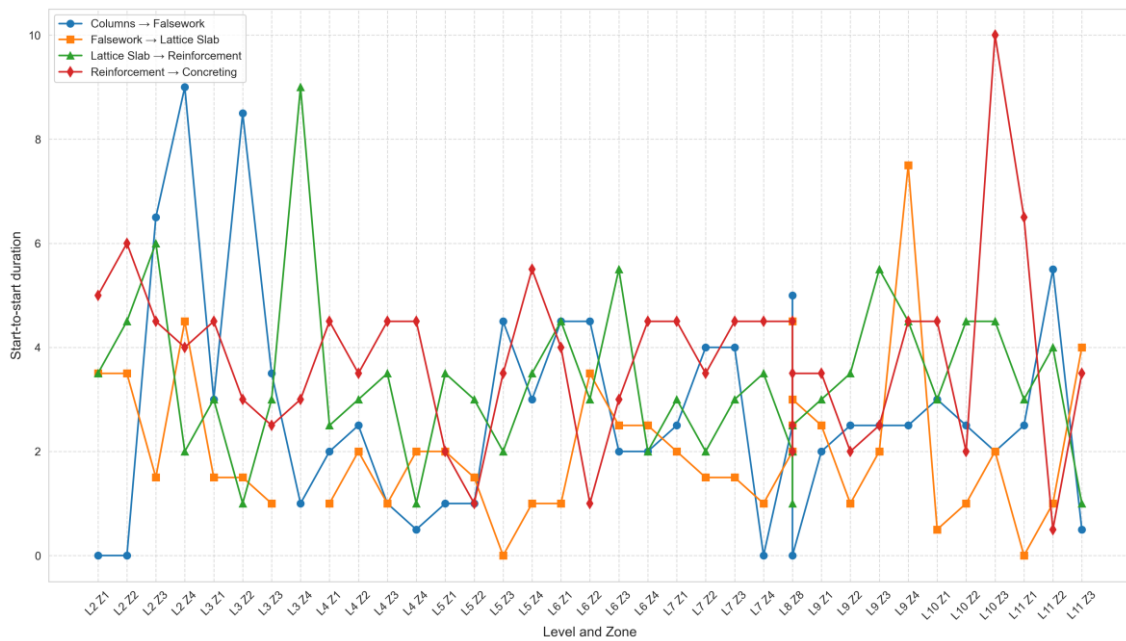


Figure 8: Variation of interface durations across levels

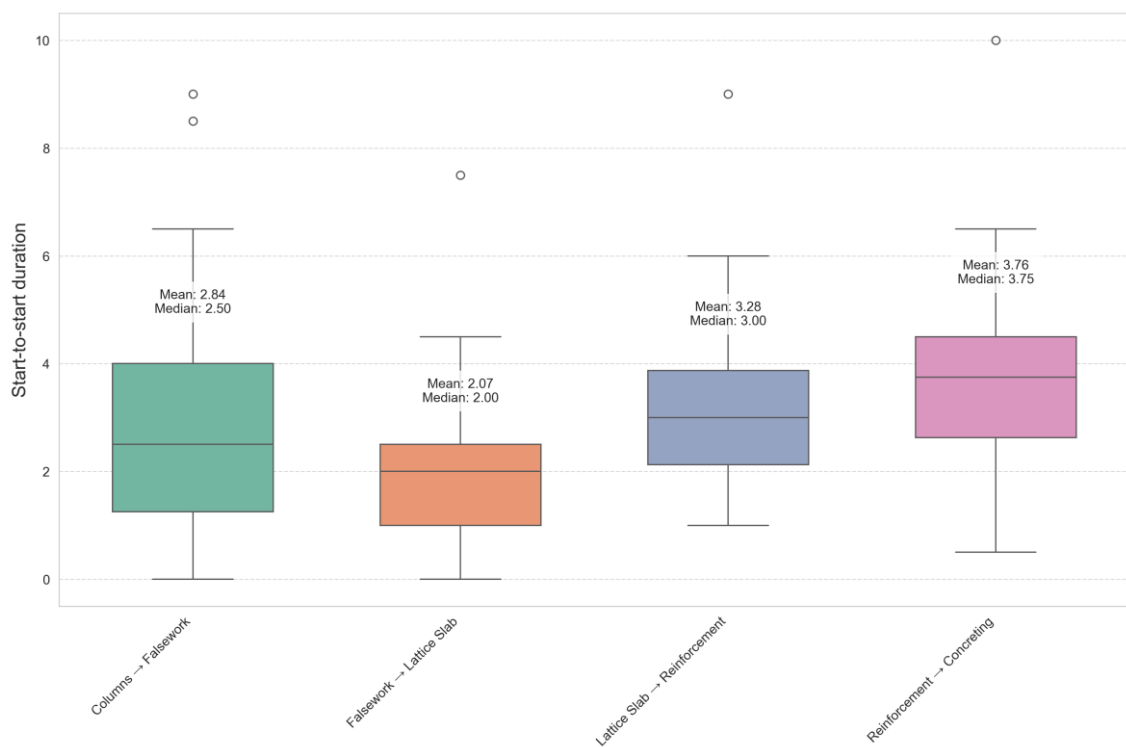


Figure 9: Distribution of star-to-start durations between zones

The results show no clear increasing or decreasing trend across levels. However, the coefficients of variation for the durations of the column-to-falsework, falsework-to-lattice-slab, lattice-slab-to-reinforcement, and reinforcement-to-concreting interfaces reveal notable differences: 0.76, 0.69, 0.48, and 0.45, respectively. The final interface, slab reinforcement to slab concreting, is the only on-site-on-site interface and exhibits the lowest variability. Furthermore, variability generally decreases across successive interfaces at each location, indicating that the initial interface between precast columns and falsework is the most critical in terms of tolerance requirements and worker unfamiliarity.

This gradient is notable: off-site-to-on-site interfaces (average $CV=0.64$) exhibit substantially greater variability than the on-site-to-on-site interface ($CV=0.45$). This pattern suggests that interface type moderates handover variability, with the manufacturing-construction boundary being particularly problematic, consistent with Pan et al. (2023).

REDUCING VARIABILITY

A key finding from the analysis is that reducing variability in both daily installation quantities and interface durations is essential to improving construction speed in off-site projects. Several underlying causes of variability were identified through interviews. While construction sites typically prefer just-in-time delivery, manufacturing facilities are not always operated with this objective in mind. A single off-site manufacturing facility may supply multiple projects simultaneously and produce components of varying dimensions and specifications. According to the manufacturing managers interviewed, factories prefer batch production, whereby identical components are mass-produced before switching to different types. This preference directly affects delivery schedules and sequences. In the case study project, although both the construction company and the precast manufacturing facility were owned by the same parent company, their operational objectives differed. This misalignment would likely be more pronounced in projects involving independent organisations. One potential solution is to use decoupling points, such as manufacturer- or contractor-managed warehouses, where bulk-produced components can be temporarily stored and released to sites in a just-in-time manner (Gosling & Naim, 2009). Second, both contractors and factory personnel highlighted the lack of an early design freeze as a major issue. Although off-site technologies have been introduced, off-site practices have not yet been fully embedded within the construction industry. All project stakeholders need to finalise designs significantly earlier to allow sufficient time for manufacturing and coordinated delivery of off-site components. Finally, as in any other project, increasing the number of working locations per floor can ensure there are always places to conduct installation work, thereby improving the construction speed of off-site projects.

DISCUSSION

THEORETICAL CONTRIBUTIONS TO LEAN IN OFF-SITE CONSTRUCTION

This study makes three theoretical contributions to lean construction theory in off-site contexts. First, while lean theory has long asserted that variability undermines performance (Koskela, 2000), empirical quantification in OSC has been lacking. The results demonstrate that the coefficient of variation (CV) and idle percentage (i.e., proportion of days without installation) are strongly and negatively correlated with production rate. This finding indicates that both metrics function as leading indicators of supply chain disruption in OSC, thereby extending the primarily qualitative insights of Arashpour et al. (2015) and suggesting that managers can monitor these indicators proactively to anticipate and mitigate performance losses. Second, the interface variability gradient, off-site-to-on-site handovers exhibiting substantially greater variability than on-site-to-on-site handovers, with progressive dampening through successive interfaces, extends interface management theory (Pan et al., 2023) by identifying interface type as a moderator of handover variability. Buffering strategies should therefore be concentrated at these boundaries and sized according to the observed CV, rather than distributed uniformly. Third, external supply chain disruptions not only reduce performance directly but also mask underlying learning effects, potentially leading to misguided managerial responses. The divergence between production rate (peaking at Level 4) and labour productivity (peaking at Level 8) demonstrates this empirically and suggests that performance tracking requires multiple metrics to distinguish between internal and external sources of variation.

IMPLICATIONS FOR PRACTICE AND LIMITATIONS

These findings refine lean implementation in off-site construction in three ways. Targeted buffering should be concentrated at off-site-to-on-site interfaces, particularly the column-to-falsework handover ($CV=0.76$). True pull systems in OSC must extend beyond single-project boundaries, requiring coordination of manufacturing capacity across multiple projects, potentially through shared decoupling points. Managers should track both production rate and labour productivity, with any divergence between them signalling supply chain issues that require intervention rather than crew-level responses. This study is based on a single case study of a residential building in the UK that uses structural frame components. As such, findings require validation through multi-case comparative studies across different project types, procurement routes, and geographical contexts. Causality is inferred through triangulation of quantitative patterns with interview data rather than through a controlled experiment. Future research should test the CV-production rate relationship across different OSC systems and evaluate the performance impact of decoupling points through intervention studies.

CONCLUSIONS

This study investigated the mechanisms constraining construction speed in off-site projects. Construction speed depended on both external and internal factors. Externally, supply chain disruptions, including factory delays driven by batch production priorities and late design information, caused out-of-sequence deliveries that could not be stored on site. These effects were captured through the CV; the proportion of non-installation days served as a useful secondary indicator, remaining visible even when day-to-day variability is not immediately apparent. Internally, the learning effect improved performance up to Level 8, while vertical transportation distances and a reduction in working locations at upper levels subsequently reduced it. Having more parallel working locations enables crews to sustain flow when individual locations experience delays.

This study provides further evidence that the physical interfaces between off-site and on-site components continue to hinder construction speed. It was found that off-site-on-site interfaces exhibited greater variability in handover durations than on-site-on-site components. Three strategies to mitigate these issues are the introduction of decoupling points (e.g., storage points between manufacturing and installation), implementation of an early design freeze to stabilise supply chain schedules and maintaining multiple work locations per floor (minimum three to four) to support parallel work and buffer against location-specific delays.

Three theoretical contributions emerge. First, CV and idle percentage (i.e., proportion of days without installation) are strongly and negatively correlated with production rate, suggesting that they are leading indicators of supply chain disruption in off-site construction. Second, the interface variability gradient reveals systematic coordination challenges at the manufacturing-construction boundary. Third, external disruptions mask underlying learning effects, explaining the divergence between production rate and labour productivity trends, and highlighting the need for multi-metric performance tracking to distinguish internal from external sources of variation.

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