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MASTER SCHEDULE OPTIMISATION WITH THE USE OF FLOWLINES AND PERFORMANCE DATA

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ABSTRACT

In the UK construction industry, Gantt charts and the Critical Path Method (CPM) are the institutionalised and accepted tools for managing construction programmes. Together with the lack of a consistent measurement framework, little is known about current productivity levels and the opportunities for improvement. Using the case of four buildings in London, this paper aims to develop a strategy to optimise the duration of master schedules using real project data and optimised production rates. Data were collected during the structural works and translated into master-level flowlines. Key performance metrics were extracted: start-to-start duration (between levels), number of concrete pours per level, batch area, and production rates. The results showed a high spread of variability in performance within and between projects. However, higher production rates are associated with shorter start-to-start durations between consecutive levels, a higher number of slab concrete pours per level, smaller batch areas, and higher prefabrication levels. The results were applied to the building with the lowest performance. Increasing the number of slab pours would reduce the programme by 39% and increase the production rate by 65%. Whilst more performance data is required to build up a robust database, these initial findings can provide contractors and clients with evidence that there is room for improvement. A client was engaged during this research and is willing to prescribe flowlines and performance metrics in future projects.

KEYWORDS

Batching, flowlines, master schedule, performance, productivity.

INTRODUCTION

In 2013, HM Government issued "Construction 2025", an industrial strategy which sets outs how the industry, represented by the Construction Leadership Council (CLC), and Government *"will work together to put Britain at the forefront of global construction over the coming years"*. The strategy set out ambitious targets including 33% lower costs, 50% faster delivery, 50% lower emissions, and 50% of improvement in exports. The presumption in favour of off-site construction, new talent and skills, digital design and smart construction, low-carbon construction, industry growth, and leadership are the core pillars of this vision. A decade on, however, there is still no clarity on whether these targets are achievable or how much progress the industry and Government have made. The presumption in favour of off-site construction has triggered several demonstrator projects and industry and academic efforts to measure

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performance. For instance, Jansen van Vuuren and Middleton (2020) published data from 46 school projects with varied levels of off-site construction. However, this study revealed that the data does not provide conclusive evidence to establish a correlation between off-site construction and improved performance. Moreover, the authors argued that there is a need to rethink how performance is measured. Bassi et al. (2022) presented data from several off-site housing projects in Bristol. Whilst programme reduction was achieved, cost reduction was not accomplished due to the small pipeline of work for manufacturers; and it is expected that cost benefits will be achievable in the future. Thus, despite the ambitious targets, there is no evidence of ongoing performance improvement.

The Construction Productivity Taskforce (CPT) is a group of major UK clients, contractors, and consultants. The CPT aims at identifying and trialling new ways of making the construction sector more productive. The authors of this paper are working with the CPT to collect, interpret, and analyse construction data to set benchmarks, identify areas for improvement, and produce new knowledge on how the industry operates. Whilst some previous research have presented case studies of lean applications in the UK construction industry (Sarhan & Fox, 2012; Drysdale, 2013; Daniel et al., 2018; Tezel et al., 2018), the reality is that major clients and contractors are unaware or have little knowledge of lean construction techniques for production planning and control. As such, the current paper uses lean construction concepts and techniques to demonstrate the potential presence of waste in the construction process and suggest possible interventions that clients and contractors can make to achieve higher levels of productivity. The scope of this research is situated at the master planning level where clients and contractors negotiate the project duration and the interdependencies between work packages. Observing potential performance improvement at the master planning level is the first level where waste can be eliminated. Consequently, further layers can be observed and analysed at the activity level as presented in the companion paper (Rathnayake et al., 2023).

This research has collected performance data from four residential and commercial buildings in London. By using high-level strategies such as batching and master-level flowlines, data were analysed quantitively to determine the causes of variability in performance within and between projects, and to demonstrate the potential performance improvement that can be achieved. The paper is structured as follows. First, a brief background is presented. Second, the case studies are described including the type of data collected. Third, the results are presented and interpreted with an emphasis on master planning duration improvement. Finally, the results are discussed, and this is followed by conclusions and a description of future work.

BACKGROUND

LEAN IN THE UK CONSTRUCTION INDUSTRY

There is some evidence in the lean construction literature that lean techniques have been implemented in the UK construction industry, particularly in highway projects from the client perspective (Drysdale, 2013). For instance, Daniel et al., (2018) showed the effect of procurement methods in the Last Planner System (LPS) implementation whilst Tezel et al., (2018) presented the results of continuous improvement and visual management techniques. Daniel et al., (2017) investigated the adoption of collaborative planning (CP) as opposed to the LPS implementation among UK contractors. The study showed that collaborative planning is a method used by contractors to plan construction activities with subcontractors with a focus on programme and time compression. As such, it lacks several components of the LPS such as the make-ready process, look-ahead planning, constraint analysis, and consideration of flow and learning. Some previous studies (e.g., Johansen & Porter, 2003) argued that the LPS can be applied to UK building constructions after the consideration of cultural barriers. For instance, subcontractors have commercial pressures from Tier 1 Contractors and "push" planning takes precedence over production and continuous flow. Moreover, commercial managers do not fully vet subcontractors' production capability and there is little consideration of the relationship between price and performance. Sarhan & Fox (2012) confirmed that UK construction organisations are far behind in a comprehensive lean approach due to the lack of awareness and understanding and suggested that large public sector clients are ahead of adoption and can incentivise the rest of the industry. Regardless of the levels of adoption, there is a void in the literature regarding performance in the UK construction sector and how this can relate to partial or full, formal or informal, implementation of lean concepts. Thus, this study aims to collect evidence from construction projects and use concepts such as flowlines and batching to identify high-level process waste and areas of improvement at the master planning level.

FLOWLINES AND MASTER SCHEDULES

Location-based scheduling model projects as a series of locations in which activities flow through different units in turn. The flowline method is a location-based scheduling method that graphically represents activities as a single line where the line passes from the lower left corner (start of location, start of duration) to the upper right corner (end of location, end of duration), and represents a crew passing through a location (Kenley & Sepännen, 2010). Moreover, it is possible to represent several crews as a fast way to model production. For the case of work packages at the master-level planning, all crews and activities can be modelled as a single line before splitting into several lines for each crew. Flowlines were used in previous research as a powerful tool for visual management in construction (Brioso et al., 2017). Lehtovaara et al., (2021) presented a client-driven project's operation strategy at the master programme level for collaborative iterations and transparent communication of construction plans. They suggested the following Key Performance Indicators (KPIs): total gross area (m^2), the quantity of work per gross area (e.g., tonnes of rebar per gross area), lead time (how fast the whole production is completed from start to finish), batch-specific lead time (how fast a batch or location is completed from start to finish), and production's tightness (average area occupied by a single worker). The authors argued that clients would drive the operations process by requiring these performance indicators in procurement which in turn would guide contractors in designing the production system accordingly. Thus, flowlines and performance indicators can be integrated to detect waste in the production system and drive performance improvement.

BATCHING

Large batches in the production system lead to an increased amount of simultaneous use of space for several tasks and result in increased lead times whereas smaller batches compress the lead time, but create vulnerability in the production system, especially in projects with high variability (Lehtovaara et al., 2021). Ward & McElwee (2007) argued that mass production is the prevalent modus operandi in the UK construction sector which is contrary to the fundamental principle of lean thinking of continuous workflow. They have shown that the concept of batch reduction or increased number of batches is not fully understood in construction and sites run on large batch areas of whole floors. After collecting data from projects, they simulated the programme savings by reducing batch areas. Maturana et al. (2003) also simulated construction scenarios and showed that the increased frequency of concrete pouring reduces workers' idle times in the structural phase of a multi-storey building. Similarly, Valente et al. (2013) showed that reducing the batch size from an entire floor to an apartment reduces the fit-out phase programme. Thus, there is evidence of potential improvements using the batching technique. However, there is little evidence of how batching drives performance during the structural phase of building projects.

METHOD

Three major residential and commercial projects in London were selected for this study. The scope of data collection and analysis was the superstructure structural frame. A summary of the buildings is presented in Table 1. These projects were considered suitable to examine performance as they depict new buildings managed by Tier 1 contractors, have a mixture of traditional in-situ and off-site construction, and were built under normal conditions (i.e., not extreme weather or stoppages). As-built construction data were collected from a variety of sources, including documents, installation reports, site visits, workshops, interviews, and access to image data such as 360 images and CCTV. Data were triangulated to ensure reliability. For instance, concrete pour installation data was reviewed using CCTV images and delivery data. The "level" was selected as the unit of analysis as opposed to the typical monthly progress measurement found in the three projects. The key independent variables extracted were:

- Gros Internal Area (GIA) in m^2 per level
- Planned & actual start date (installation of the first vertical element on the level)
- Planned & actual end date (last concrete pour on the level)
- Number of horizontal concrete pours per level
- Average Batch area per pour (m^2)
- Level of prefabrication (dummy variable 0: Null; 1: High).

Flowlines was selected as the tool to visualise the master-level programme with a location breakdown structure on a level-by-level basis. The rationale for this was the need to present to construction stakeholders, who are mostly familiar with Gantt Charts, a better tool to visualise and understand the actual construction programme and the relationships and interdependencies of timeframes between consecutive levels. The following outcome variables were extracted:

- Production rate: the GIA divided by the planned/actual duration per level
- Start-to-start duration: the duration between the start date of two consecutive levels.

Quantitative methods such as correlation analysis and multiple regression were applied to the data to deduce the relationships and dependencies between the variables.

Table 1: Case studies description (note that A & B are from the same project)

Building	Use	Levels	Structural frame
A	Offices	9	Twin walls, structural steel, in-situ slab concrete pour
B	Offices	9	Twin walls, structural steel, in-situ slab concrete pour
C	Offices	11	Traditional in-situ reinforced concrete
D	Residential	12	Offsite components, in-situ slab concrete pour

RESULTS

The first step in the data analysis was to calculate the planned and actual production rates. Figure 1 presents a plot with the results. Each data point represents a level. All data points above the diagonal show that the actual outperformed the plan whereas all data points below the diagonal indicate that the actual underperformed the plan. It is noteworthy to highlight that the number of data points above the diagonal is far less than the data points under the diagonal. Moreover, the data points above the diagonal hardly exceed the planned performance whereas the data points below the diagonal are far below the expected performance. Thus, these projects show significant performance issues that must be understood to improve productivity.

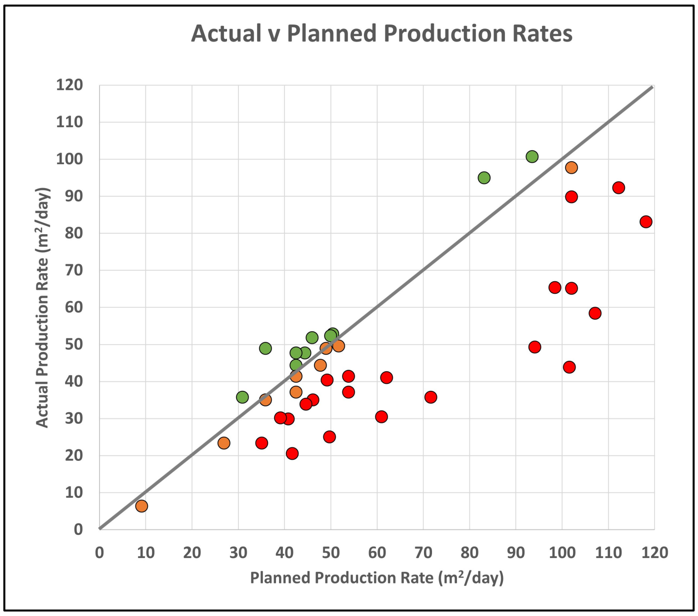

Figure 1: Planned versus actual performance (all buildings)

Table 2 presents the results for production rates, start-to-start durations, number of pours and average batch area for all buildings. Buildings A and B have 1 or 2 pours per level and the biggest batch area (> 600 m^2) which are associated with the highest start-to-start average durations and the lowest overall production rates. The number of concrete pours and batch area are well-known parameters to improve the performance of the production system (Valente et al., 2013; Ward & McElwee, 2007; Alves & Tommelein, 2004). However, these concepts were not fully implemented in the projects under study.

Table 2: Summary of Results

Variables	Unit	A	B	C	D
Production rate (PR)					
Minimum	m^2/day	23	23	21	44
Maximum	m^2/day	49	49	53	101
Median	m^2/day	40	39	32	74
Overall	m^2/day	46	31	59	115
Start-to-start duration (St-to-st)					
Minimum	day	20	20	10	8
Maximum	day	38	28	29	23
Median	day	26	24	14	10
Pours per level (Pours)	-	2	1	3	4
Batch area (Batch)	m^2	619	668	300	357
Prefabrication (0 = No; 1 = High)	-	1	1	0	1

Master-level flowlines

From a master schedule point of view, the aim is to shorten the overall lead time by 1) reducing the start-to-start duration between levels and 2) maximising the level-by-level production rates. Figure 2 presents the master-level actual flowlines of building A and the associated production rates. The highest production rate was achieved in level 7 (49 m^2/day) whereas the lowest production rate was in level 9 (23 m^2/day). The overall production rate of 46 m^2/day is the building's GIA divided by the overall duration. On the other hand, the highest start-to-start duration was between levels 1 and 2 (38 days) whereas the lowest start-to-start duration was between levels 6 & 7 and 7 & 8 (20 days). Moreover, Figure 2 shows an overlap between consecutive levels. This overlap was described by Kenley & Sepännen (2010) as *splitting* which is the result of breaking the work into sections to improve production. Using the metaphor of a *telescope*, the aim is to shorten the telescope by increasing the overlaps between levels. However, Building A had the bigger batches, the longer start-to-start durations and thus, the less overlap or *splitting* between levels.

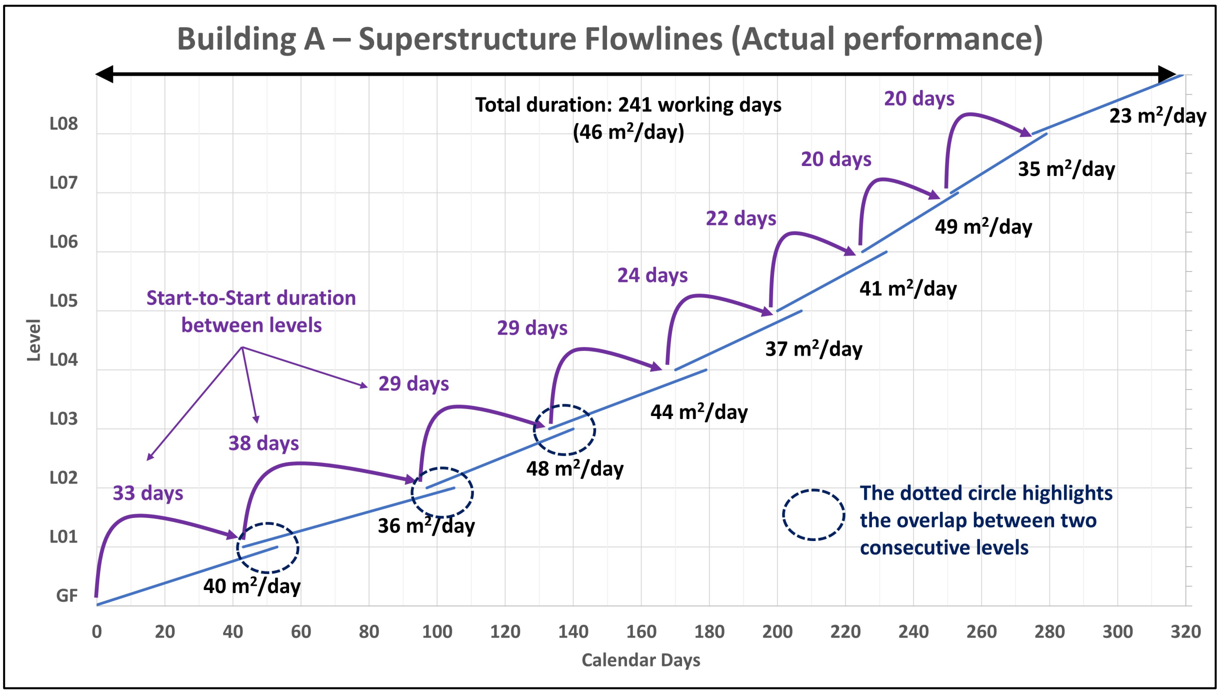

Figure 2: Master-level flowlines for the superstructure of Building A

LOOKING FOR PATTERNS IN THE DATA

Table 3 presents the results of the correlation analysis of the pooled dataset. The results show that 'Production Rate' is significantly correlated to 'Start-to-start duration' ($r=-0.602$, $p<0.01$), 'Number of pours' ($r=0.527$, $p<0.01$), and 'Prefabrication' ($r=0.497$, $p<0.01$). However, there is not a significant correlation between 'Production Rate' and 'Level' or 'Batch area'. Moreover, 'Start-to-start duration' is significantly correlated to 'Number of pours' ($r=-0.537$, $p<0.01$), 'Batch area' ($r=0.700$, $p<0.01$), and 'Level' ($r=-0.436$, $p<0.01$). Nonetheless, there is not a significant correlation between 'Start-to-start duration' and 'Prefabrication'.

To further understand the relationships between these variables, Figure 3 presents the plots of the first dependent variable of interest, production rate, against start-to-start duration, number of pours, batch area, and prefabrication. First, the highest production rate (80 m^2/day and above) is associated with start-to-start duration values between 9 and 12 days. However, these are also associated with production rates below 60 m^2/day. Nonetheless, a start-to-start duration of 20 days and above are *only* associated with production rates below 60 m^2/day. Second, there is an upward trend between the number of pours and the production rate with values above 80 m^2/day with 4 and 5 pours, whilst 3 or fewer pours achieve 60 m^2/day or less. Third, a batch area between 330 and 420 m^2 is associated with the highest production rates. Surprisingly, batch areas under 300 m^2 are associated with lower production rates comparable with a batch area of 500 m^2 or more. However, a closer examination shows that these data points correspond to unusual levels such as level 1, which in most cases were transfer slabs or the top levels which correspond to complex structures in the roof. Thus, the variability of the data does not support any potential relationship between the batch area and the production rate. Finally, projects with the highest levels of prefabrication (dummy variable = 1) are associated with the highest production rates whilst the lowest production rates are associated with projects without off-site components (dummy variable = 0).

Table 3: Correlations between variables (** p<0.01)

	Level	St-to-St	PR	Pours	Batch	Prefab
Level	1.000					
St-to-St	-0.436**	1.000				
PR	-0.146	-0.602**	1.000			
Pours	-0.099	-0.537**	0.527**	1.000		
Batch	-0.434**	0.700**	-0.113	-0.658**	1.000	
Prefab	0.023	-0.032	0.497**	-0.173	0.479**	1.000

Figure 3: Relationship between production rate and variables under examination

Figure 4 depicts the plots of the second dependent variable of interest, start-to-start duration, number of pours, batch area, prefabrication, and level. First, batch area and start-to-start duration show a high linear correlation. A batch area of 400 m^2 or below is associated with the lowest start-to-start durations. Second, there is a modest relationship between the number of pours and start-to-start duration. For instance, 3 to 5 pours are associated with the lowest start-to-start durations whilst 1 to 2 pours are associated with values of 20 days and above. Third, there is not a clear relationship between prefabrication and start-to-start duration although values of 10 days and above are only achieved in prefabricated projects (dummy variable = 1). Finally, there is a downward linear trend between level and start-to-start duration. Moreover, values between 10 and 15 days happened across all levels. Thus, this is an indication that level is not a predictor of start-to-start duration.

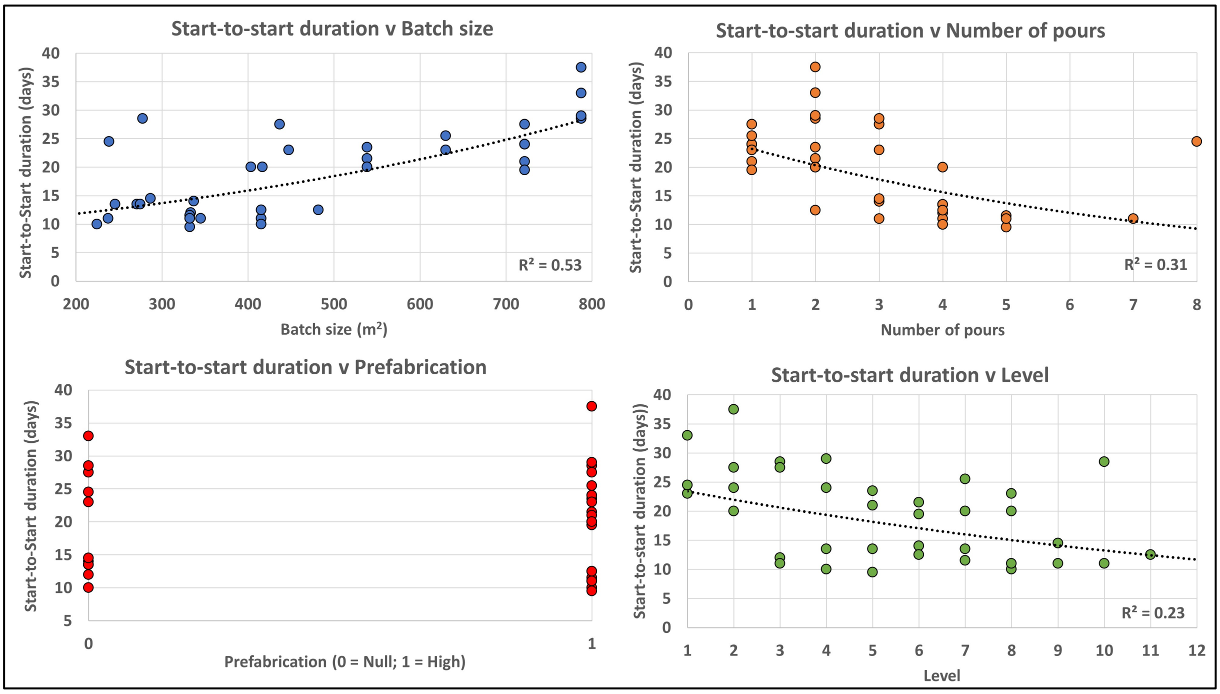

Figure 4: Relationship between start-to-start duration and the variables under examination

MULTIPLE REGRESSION ANALYSIS

A multiple regression analysis was conducted to model the production rate and the start-to-start duration. The results in Table 4 show that start-to-start duration, prefabrication, and the number of pours explain 69% of the variance of production rate whereas batch area was not found to be a significant predictor. These results suggest that all things being equal, every additional start-to-start day reduces the production rate by 0.8 m^2/day. Moreover, projects with a high level of prefabrication perform 26 m^2/day higher than projects without prefabrication. Finally, every additional pour (or batch) per floor increases the production rate by 6.5 m^2/day. Moreover, the results also show that batch area and prefabrication explain 61% of the variance of start-to-start duration whilst the number of pours and level were not found to be significant predictors. These results suggest that all things being equal, every additional 100 m^2 of a batch area increases the start-to-start duration by 3.6 days. Moreover, projects with a high level of prefabrication have 7 start-to-start days shorter compared to projects without prefabrication.

Table 4: Multiple regression results (N=40)

Variable	β	SE	t	p-value
Dependent variable: Production Rate (R^2=0.693)				
Constant	28.633	10.137	2.825	0.008
Start-to-start duration (St-to-St)	-0.832	0.317	-2.622	0.013
Prefabrication (Prefab)	26.220	4.349	6.029	0.000
Number of pours (Pours)	6.485	1.497	4.331	0.000
Dependent variable: Start-to-start duration (R^2=0.606)				
Constant	6.483	2.100	3.086	0.004
Batch area (Batch)	0.036	0.005	7.539	0.000
Prefabrication (Prefab)	-7.148	1.851	-3.861	0.000

These results suggest that at the master level planning, the strategy to increase the production rates is to reduce the start-to-start duration and increase the number of pours per level. In turn, the strategy to reduce the start-to-start duration and increase the number of pours is to reduce the batch area. Moreover, prefabrication has a significant impact on reducing the start-to-start duration and increasing the production rate. In summation, the outcome variables of interest can be explained by the data and planners can consider these relationships during the structural frame's production system design at the master programme level with the use of flowlines.

PERFORMANCE IMPROVEMENT

The next step in the methodology is to use the performance data results to simulate potential optimisation scenarios at the master programme level and assess whether production rates and programme durations can be improved. To do this, building A was selected due to the presentative GIA, the lower number of pours per level, and the lower production rates compared to buildings C and D. Table 5 presents the results of this process. The first step is to increase the number of pours to assess its effect on the production rates and start-to-start durations. For instance, 4 pours of approximately 394 m^2 were selected for levels 1 to 4, whilst 3 pours of approximately 359 m^2 were selected for levels 5 to 7. The estimated start-to-start duration is calculated using the multiple regression results indicated in Table 4 using the batch area (m^2) and prefabrication (0 = null, 1 = high). The estimated start-to-start durations are shown in Table 5 and the actual values achieved onsite are shown in parentheses. Thus, there is a substantial reduction in the start-to-start values which is in line with potential programme reduction. Similarly, the optimised production rate was calculated using the multiple regression results presented in Table 4. The estimated level-by-level production rates are shown in the last column of Table 5 and the actual values achieved onsite are shown in parentheses. Thus, there is a substantial production rate improvement between levels 2 and 8. Finally, the level duration was estimated using the estimated production rate and the GIA. The estimated durations are shown in Table 5 whilst the actual performance is shown in parentheses. For levels 2, 3, and 4, the estimated duration is 23 days which is a substantial improvement from 44, 33, or 36 days.

Table 5: Master programme optimisation results (Building A)

Level	Batch	Batch area	Prefabri cation	Start-to-start duration: Estimated (Real)	Level duration: Estimated (Real)	Production rate: Estimated (Real)
1	4	394	0	21 (33)	42 (39)	37 (40)
2	4	394	1	14 (38)	23 (44)	69 (36)
3	4	394	1	14 (29)	23 (33)	69 (48)
4	4	394	1	14 (29)	23 (36)	69 (44)
5	3	359	1	14 (24)	17 (29)	64 (37)
6	3	359	1	12 (22)	17 (26)	64 (41)
7	3	359	1	12 (20)	17 (22)	64 (49)
8	2	404	1	14 (20)	14 (23)	56 (35)
9	2	404	0	N/A	33 (35)	24 (23)

Finally, Figure 5 presents the overlay of the actual flowlines and the potentially optimised flowlines. The flowlines show that the superstructure programme is shortened from 241 to 146 working days, a reduction of 39%. Similarly, the overall production rate increases from 46 to 76 m^2/day; an improvement of 65%.

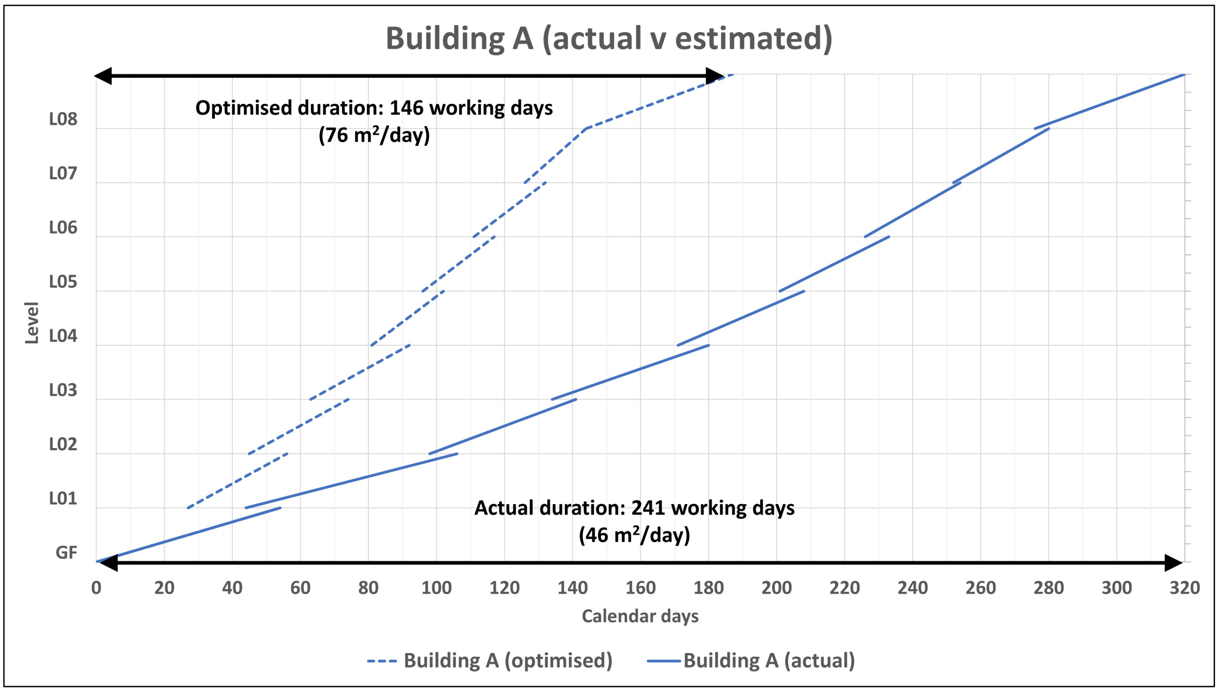

Figure 5: Actual v optimised flowlines for the superstructure (Building A)

DISCUSSION

Data were collected and analysed retrospectively and presented to the industry partners involved in this research. Therefore, the interpretation of the data and the identification of high-level strategic variables is pivotal for understanding what is going on and making decisions. Contractors typically report the SPI (schedule performance index) from the Earn Value Management methodology. This research has shown that additional high-level metrics are needed to compare actual performance, identify the gaps with plans, and look for improvement opportunities. Industry partners who were unfamiliar with flowlines have identified the tool as a powerful means to communicate master programmes, scrutinise the start-to-start durations between consecutive levels, and decide on the best production rates applicable to the project. The use of historical data is fundamental for benchmarking.

First, the data has shown substantial performance issues that were unknown or not fully understood by project stakeholders. The visualisation of master-level flowlines and the level-by-level basis production rate stand in sharp contrast with the weekly or monthly SPI. SPI only shows whether the project is ahead of time or delayed, whereas the production rates are leading indicators that can be timely presented to detect productivity issues. Moreover, the effect of batching on production rates and start-to-start duration becomes clearer. For instance, building D has the shortest average start-to-start duration (10 days) and the highest production rate (115 m^2/day) whereas building A has the longest average start-to-start duration (26 days) and one of the lowest production rates (46 m^2/day). These are associated with the number of batches and the batch area. Furthermore, the iteration of these variables in the early stages of planning can improve the overall slope of the work package's flowline and thus determine the optimum duration. This level of interpretation is certainly difficult to achieve with traditional Gantt charts, as expressed by several project stakeholders.

Second, lean techniques or the Last Planner System (LPS) were not implemented in these projects. However, the concept of batching was tacitly implemented in buildings C and D. Some stakeholders argued that in the UK construction industry, there is a central logic that can be expressed as *"the larger the concrete pour, the better."* This was demonstrated in buildings A and B which had 2 and 1 pours respectively, making it impossible to shorten the start-to-start durations and optimise performance. This logic reflects that planners and supply chain value larger pours to optimise resources on the pour day. This finding was also highlighted in 2007 by Ward & McElwee who argued that the UK construction sector works to large batch sizes to ensure continuity of the same activity for as long as possible. The site logistics of Buildings A and B did not indicate a specific requirement for one or two batches, thus, it was a management decision underpinned by this logic. Moreover, Tier 1 Contractors do not have enough visibility of the construction flows, crew utilisation, and performance issues of their subcontractors. For instance, subcontractors mobilise personnel between projects and send more workers to the site on pour days to meet the contractor's programme. Building D, however, had in-house workers. The contractor maximised labour utilisation by having multi-skilled labourers who can perform several activities to ensure workflow continuity.

Third, more data granularity is needed to understand the differences within projects. The companion paper (Rathnayake et al., 2023) presents data at the activity level and shows that the excess of work-in-progress time had a significant influence on production rates. Moreover, there is an opportunity here to implement the LPS and correlate the PPC metric and reasons for non-completion with master-level production rates. In this research, some performance issues were detected from CCTV cameras and weekly reports. However, these were not captured consistently to ensure a thorough understanding of what went wrong and why. Finally, the variables used in this research are in hands of planners and project managers (i.e., how many batches, batch size, start-to-start duration, and prefabrication). This presents an opportunity to develop a causal model using larger datasets that can inform optimised parameters for new construction programmes. Additionally, this model can be utilised to simulate the performance of new projects, enabling planners the consideration of multiple scenarios for decision-making.

CONCLUSIONS

This research proposes an approach to analyse as-built construction data using master-level flowlines with the aim of optimising project duration. The study collected empirical data from four large buildings located in London. The results of the analysis indicated a significant disparity between planned and actual production rates. To address this issue, master-level flowlines were developed and presented to project stakeholders to improve their understanding of the construction process and ultimately enhance project performance. Two performance metrics were selected to optimise the duration of the work package: start-to-start duration (between levels) and production rates. The results showed a high spread of variability in the performance data within and between projects. However, higher production rates are associated with shorter start-to-start durations, a higher number of slab pours per level, smaller batch areas, and higher prefabrication levels. The results were applied to the building with the lowest performance. Increasing the number of pours from 2 to 4 would reduce the programme by 39% and increase the production rate by 65%. Whilst more performance data is required to build up a robust database, these initial findings can provide contractors and clients with evidence that there is room for improvement. The client was engaged during this research and is willing to prescribe flowlines and performance metrics in future projects. Finally, this work can also be extended to the analysis of the relationships between the superstructure and the next work packages such as cladding and fit-out. The review of the work in progress between work packages, start-to-start durations between levels, and production rates could drive significant performance improvement for the entire project and therefore achieve industry aspirations.

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