Rathnayake, A., Murguia, D. & Middleton, C. (2023). Analysing the impact of construction flow on productivity. *Proceedings of the 31st Annual Conference of the International Group for Lean Construction (IGLC31),* 1510–1521. doi.org/10.24928/2023/0172

ANALYSING THE IMPACT OF CONSTRUCTION FLOW ON PRODUCTIVITY

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ABSTRACT

Construction is one of the least productive industries. A significant reason for this is not viewing the construction process as a combination of flows, i.e. continuous streams of workers, materials or equipment. This paper aims to improve our understanding of construction flow by demonstrating how it can be quantified and how its impacts on productivity can be measured. We discuss two main types of flow: 1) process/location flow, representing the flow of activities performed at a single location and 2) operations/trade flow, representing the activities performed by a single trade through different locations. Based on the literature, we develop a set of metrics for each type of flow. Then, we measure their influence on productivity by using data from four buildings' superstructure work packages. The process flow is compared with the productivity of individual locations, and the operations flow is compared with the productivity of separate crews. The results show that the excess work-in-progress time between successive crews and the mean and variability of production rates for different crews at each location (process flow metrics) can explain 72% of the variation in location productivity. Similarly, the level of work discontinuity (operations flow metric) can explain 52% of the variation in trade productivity. We believe this paper presents convincing evidence of the importance of construction flow in improving productivity.

KEYWORDS

Flow, productivity, work in progress/process (WIP), variability, resource continuity

INTRODUCTION

Productivity, defined as the ratio of output to input, is an indicator of efficiency. The construction industry is globally known for being one of the least productive sectors (Barbosa et al., 2017). This is reflected in the UK's construction industry, which has only shown a 1% improvement in productivity (measured as the gross value added per hour worked) on average from 1997 to 2021. In contrast, the manufacturing sector and the whole economy have improved by 182% and 29%, respectively, in the same period (ONS, 2023). Productivity is a means to an end and not an end in itself. Low productivity indicates low performance in other areas, such as cost overruns, schedule delays and high carbon emissions. Therefore, identifying the underlying reasons for low productivity can help address a number of performance issues affecting the construction industry.

Koskela (1992) argued that traditional managerial methods, such as critical path models, often overlook non-value-adding activities leading to low productivity in construction. The

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author suggested viewing construction as a flow of material and/or information from raw material to the end product. Flow can be defined as a continuous stream of something (Kalsaas & Bølviken, 2010). The lean literature discusses different types of flow, including workflow, worker flow, material flow, equipment flow, trade flow, assembly flow, operations flow, process flow, product flow, information flow and portfolio flow (Tommelein et al., 2022). Some of these flows are incorporated into lean managerial practices.

Despite the efforts of the lean construction community to popularise the concept of flow, a recent survey conducted among construction practitioners from the US, China, Brazil and Finland found that nearly half of the respondents relied only on traditional Critical Path Method-based systems for project management (Olivieri et al., 2019). This shows that the construction industry is yet to fully embrace the concept of flow. There have been efforts to define (Sacks, 2016) and quantify (Sacks et al., 2017) the impact of different types of flow on project performance. However, the impact of flow on project performance has not been adequately measured, highlighting a research gap that needs to be addressed. This paper aims to fill this gap by providing quantitative evidence of how different aspects of construction flow affect performance. We use productivity as an indicator of overall performance.

CONSTRUCTION FLOW

MAIN TYPES OF CONSTRUCTION FLOW

Modern ideas about construction flow derive from the concepts of production flow in manufacturing. More specifically, they can be traced back to the Toyota Production System, which is a system of increasing production efficiency by eliminating waste. It was developed by the Japanese automobile manufacturer Toyota during the mid-20th century (Ohno, 1988). As part of this system, Shingo and Dillon (1989) defined production as a combination of processes and operations. In other words, there are two types of flow in a manufacturing process: 1) process flow which represents the flow of material in time and space, transforming from raw materials to the finished product and 2) operations flow which represents interaction and flow of equipment and operators in time and space, to accomplish the transformation. This distinction is necessary because operation improvements made without considering the process can lead to overall inefficiencies (Shingo & Dillon, 1989).

The concepts of process and operation need to be re-evaluated in the context of construction. Unlike in manufacturing, the construction product is stationary, and the workstations (workers or equipment) move from location to location (Bertelsen et al., 2007). Hence, construction can be introduced as a combination of two types of flow: 1) process/location flow, which represents the flow of activities performed at a single location and 2) operations/trade flow, which represents the activities performed by a single trade through different locations (Sacks, 2016; Tommelein et al., 2022). Simply put, operations flow concerns how individual construction activities can be done faster, whereas process flow concerns how different activities can be sequenced better to improve overall speed. For the rest of the paper, we focus on these two types of flow.

FEATURES OF A GOOD CONSTRUCTION FLOW

According to Koskela (1992), the purpose of visualising construction as a flow is to reduce non-value-adding activities such as moving, waiting and inspecting. In this section, we examine a few concepts that can be used to achieve this, derived mainly from the field of manufacturing.

Optimum Batch Size

In manufacturing, batch size (more specifically, the transfer batch size) is the number of products accumulated at a workstation before being transferred to the next station (Hopp & Spearman). According to Little's law (Hopp & Spearman, 2011; Little & Graves, 2008), as the number of products accumulated at all the workstations in a steady-state production system is gradually increased, two observations are made: 1) the time spent by a product stays constant until a certain point and starts increasing and 2) the rate of output of the entire process increases until the same point and stays constant. If all the workstations produce the same output per unit of time, this optimal point is achieved when the total number of products is equal to the number of machines, i.e. batch size equals one (Hopp & Spearman, 2011).

In construction, having too many products in the process equates to having too many unfinished locations. Following the manufacturing argument, if all the crews in a project generated the same output per unit of time, it would be good to have the number of unfinished locations in the process to be equal to the number of crews, leading to a batch size of one for each crew. However, the steady-state assumption is usually invalid for construction as the production rates of different crews change over time and production durations are limited by project size (Walsh et al., 2007). Hence, more variables are needed to define a good construction flow for real-world conditions. We define a few such variables in the following two subsections.

Less Variability

Variability is the quality of non-uniformity of a class of entities (Hopp & Spearman, 2011). The ideal scenario of a batch size of one introduced in the previous subsection is an average value, as Little's law deals with averages. Real-world systems almost always have variability (Hopp & Spearman, 2011; Little & Graves, 2008). We can explain the importance of this for construction as follows. In a project, the work done by one crew, e.g. slab formwork, usually feeds another crew, e.g. slab reinforcement. If one crew has high variability, their production rate may be fast one time and slow another time. When they are fast, they will go through the entire location and end up idle until the upstream crew can release the following location. When they are slow, the crew will hold up a location making the downstream crew idle. Both these scenarios lead to a loss of productivity. This is true even when each crew produces the same average output per unit of time, and each crew has a batch size of one. According to the previous subsection, for projects obeying Little's law, these two conditions should lead to optimum productivity. However, in real projects, variability can have a detrimental effect on productivity.

Hopp & Spearman (2011) discussed two types of variability: 1) variability which occurs at individual workstations and 2) variability which occurs between the transfer of jobs or parts from one station to another. These two correspond to the operations flow and process flow we defined earlier. Variability is quantified as the coefficient of variation, i.e. the ratio of standard deviation to mean, of the operation time (time per location) or arrival rate (locations per unit time). Less variability is an indication of a good construction flow.

Less Excess Work-in-progress Time

In manufacturing, work-in-progress is the total inventory between the start and end of a process (Hopp & Spearman, 2011). Unlike the ideal scenario of a batch size of one introduced earlier, real-world systems may have larger batch sizes (leading to higher work-in-progress) to reduce setup times, as buffers or due to other reasons. Buffers can include inventory, time and capacity allowances to account for the variability discussed earlier (Hopp & Spearman, 2011). In construction, additional or standby resources have to be allocated to address risks. We define excess work-in-progress time as the time corresponding to the additional inventory between two crews that could have been avoided. According to the manufacturing principles introduced above, less excess work-in-progress time is an indication of a good construction flow.

Low Level of Work Discontinuity

Planning for continuous resource use helps maximise productivity and is one of the primary objectives of location-based scheduling (Kenley & Seppänen, 2010). Here, resources include workers and equipment. Perfect continuity is achieved if a particular location starts just after finishing the preceding location with no break. However, in reality, discontinuities occur between successive levels. Besides the apparent loss of productivity due to not working, discontinuous work also increases schedule risk as the crews may not return to work or crew compositions may change (Seppänen & Kankainen, 2004). We identify that resource/work continuity corresponds to a good operations flow.

METHODOLOGY

The aim of this investigation is to identify how construction flow affects the overall productivity of a project and demonstrate how these results can be used to interpret and improve productivity. The research methodology consists of three steps: 1) defining the parameters, 2) collecting project data and 3) analysing the data.

DEFINING THE PARAMETERS

Productivity Metrics

The literature presents various productivity metrics that extend beyond the conventional labour productivity measure. For a thorough and comprehensive summary of these metrics, readers are encouraged to refer to Rathnayake and Middleton (2023). In this study, our focus centres on evaluating the efficiency of the entire crew rather than individual labourers. Hence, we used production rate, i.e. the ratio of output to time, as the indicator of productivity.

Two metrics, overall location production rate and overall trade production rate, are used as the dependent variables of process flow and operations flow metrics, respectively. We define them in Tables 1 and 2. Both metrics use the unit of square metres of floor area per day. For process flow, locations with different floor areas need to be compared. The reciprocal of the production rate is the time taken to complete 1 m^2 of floor area, which is a relative measure. Hence, no adjustment is needed to allow comparison. For operations flow, different activities need to be compared. Using the common output of floor area allows this.

Process Flow Metrics

Table 1 presents the process flow metrics we used in our analysis. They are based on the features of a good construction flow mentioned earlier. All the metrics are scaled to allow comparison among different locations and between projects. Both process and operations flow metrics use floor area instead of time for scaling, as floor area is the constant defining factor of a location or a building, whereas time can vary. Figure 1 visually represents the metrics of a hypothetical project in a flowline chart. A flowline chart is the most common tool to visualise the flow of work through locations. Each activity is represented by a line where the X-axis corresponds to time and the Y-axis corresponds to locations. The process flow advances through time at each location. Blue, green and red lines represent activities 1, 2 and 3 performed by crews 1, 2 and 3, respectively.

The average batch size of a location is calculated as follows (see Figure 1). Consider activity 1 (in blue), which takes nine days to be completed in location 1 ($t_{1,1}$). For the first five days of this period, only location 1 has unfinished work. For the next four days, both locations 1 and 2 have unfinished work. This gives an average of (1*5 + 2*4)/9 = 1.44 unfinished locations during this period. Similarly, the time taken to complete activity 2 at location 1 ($t_{1,2}$) is 16, and the average number of locations with unfinished work during this period is 1.75. $t_{1,3}$ is 1, and the average number of locations with unfinished work is 1. If this is considered a factory, each location corresponds to a product, and each crew corresponds to a workstation. $t_{1,1}$ is the time spent by location 1 being worked on by crew 1. The average number of unfinished locations of crew 1 during that period is the batch size of crew 1 in the process. Similarly, crews 2 and 3 have their own batch sizes. The average batch size of the entire construction process at location 1 is the weighted average of these different batch sizes with respect to time which is then scaled to the floor area, i.e. $((1.44*t_{1,1} + 1.75*t_{1,2} + 1*t_{1,3})/ t_{1,all})/a_1 = ((1.44*9 + 1.75*16 + 1*1)/25)/a_1 = 1.68/a_1$.

The hands-off duration between two consecutive activities is normally defined by the takt-time in the production system design (Frandson et al., 2014). Since the projects under consideration did not formally implement takt-time planning or similar methods, it is difficult to determine the excess work-in-progress times (i.e. durations beyond the takt-time). As an alternative, we assumed that the lowest work-in-progress time maintained by a location with respect to its area is the minimum required time for that building. The rest of the locations are analysed relative to the lowest time (with respect to its area) for the building, i.e. $(w/a)_{min}$.

Table 1: Process/Location Flow Metrics

Metric	Definition	Calculation (See Figure 1)	Unit of Measurement
Average batch size	The ratio of the weighted average batch size of crews at a location to the floor area. Batch size is the average number of unfinished locations worked on by a crew between the start and end dates of a location	Explained above	$1/m^2$
Variability of location production rates	Coefficient of variation of all crew production rates in one location	(Standard deviation of $a_1/t_{1,1}$, $a_1/t_{1,2}$, $a_1/t_{1,3}$)/ (Mean of $a_1/t_{1,1}$, $a_1/t_{1,2}$, $a_1/t_{1,3}$)	Unitless
Excess work-in-progress time	The ratio of the total time between the start of each successive activity and the floor area of a location minus the lowest value for the entire building	$(w_{1,12} + w_{1,23})/a_1 - (w/a)_{min}$	$days/m^2$
Mean location production rate	Mean of all crew production rates in one location	Mean of $a_1/t_{1,1}$, $a_1/t_{1,2}$, $a_1/t_{1,3}$	m^2/day
Overall location production rate (dependent variable)	The ratio of the floor area to the total duration of a location	$a_1/t_{1,all}$	m^2/day

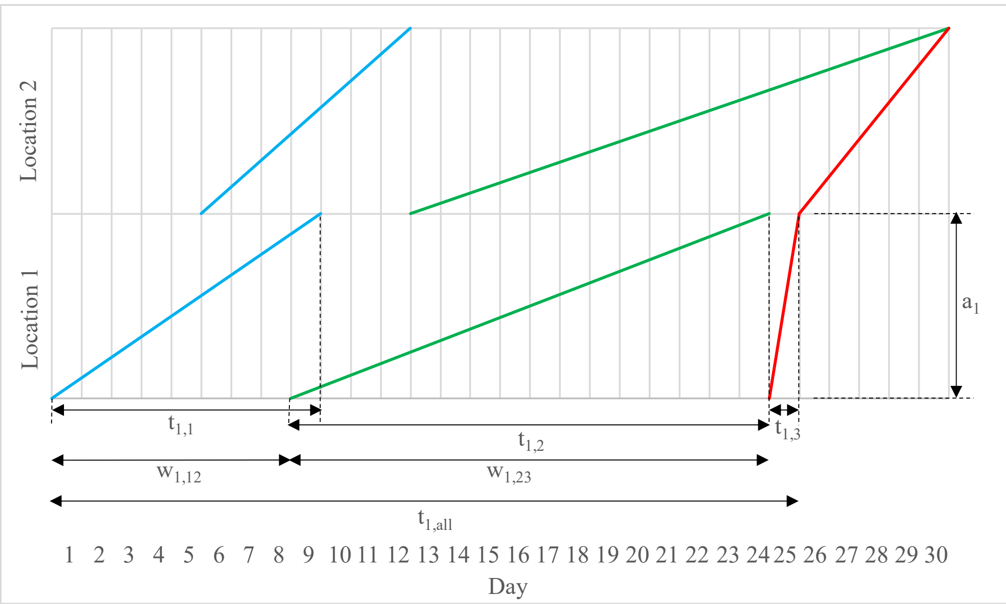

Figure 1: Calculating Process Flow Metrics

a_1 = floor area of location 1
$t_{1,all}$ = time taken to complete location 1
$t_{1,1}$, $t_{1,2}$, $t_{1,3}$ = time taken to complete activities 1, 2 and 3 at location 1
$w_{1,12}$, $w_{1,23}$ = time corresponding to work-in-progress between activities 1, 2 and 2, 3 at location 1

Operations Flow Metrics

Table 2 presents the operations flow metrics we used in our analysis. Figure 2 visually represents the metrics of a hypothetical project in a flowline chart. The four blue lines represent an activity performed by a crew in four locations. The operations flow advances diagonally along flowlines as the trade moves through each location.

Table 2: Operations/Trade Flow Metrics

Metric	Definition	Calculation (See Figure 2)	Unit of Measurement
Level of work discontinuity	The ratio of total time spent by a crew without working in between locations to the total floor area of the building	$(d_{12,1} + d_{23,1} + d_{34,1})/ (a_1 + a_2 + a_3 + a_4)$	days/m^2
Variability of trade production rates	Coefficient of variation of one crew's production rates in all the locations	(Standard deviation of $a_1/t_{1,1}$, $a_2/t_{2,1}$, $a_3/t_{3,1}$, $a_4/t_{4,1}$)/ (Mean of $a_1/t_{1,1}$, $a_2/t_{2,1}$, $a_3/t_{3,1}$, $a_4/t_{4,1}$)	Unitless
Mean trade production rate	Mean of all location production rates by one crew	Mean of $a_1/t_{1,1}$, $a_2/t_{2,1}$, $a_3/t_{3,1}$, $a_4/t_{4,1}$	m^2/day
Overall trade production rate (dependent variable)	The ratio of the total floor area of all the locations to the total duration taken by a crew to complete them	$(a_1 + a_2 + a_3 + a_4)/ t_{all,1}$	m^2/day

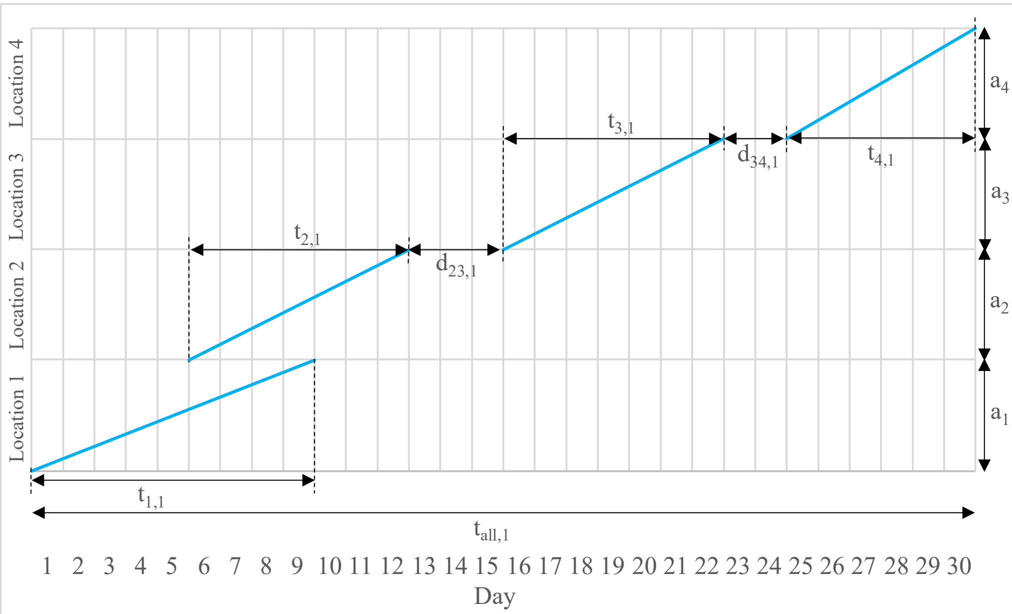

Figure 2: Calculating Operations Flow Metrics

a_1, a_2, a_3, a_4 = floor areas of locations 1, 2, 3 and 4
$t_{all,1}$ = total time between the start and end dates of crew 1 in the four locations
$t_{1,1}$, $t_{2,1}$, $t_{3,1}$, $t_{4,1}$ = time taken to complete locations 1, 2, 3 and 4 by crew 1

$d_{12,1}$, $d_{23,1}$, $d_{34,1}$ = discontinuities between locations 1,2; 2,3 and 3,4 for crew 1
Note that $d_{12,1}$ is 0 because work commenced at location 2 before finishing at location 1.

COLLECTING PROJECT DATA

We used installation and labour data from the superstructure construction of four buildings in London. Buildings A and B are eight-story buildings with steel frames and in situ concrete slabs. Their total gross internal areas are about 10,400 m^2 and 5,700 m^2, respectively. Building C is an eleven-story building with a traditional reinforced concrete structure. Its total gross internal area is about 14,200 m^2. Building D is a fourteen-story building with precast columns and lattice slabs. Its total gross internal area is about 19,000 m^2. A, B and C are commercial buildings, whereas D is residential. The first level of buildings A, B and D were not considered because they used different structural systems with separate activities and crew arrangements. Levels 10 and 11 in Building C and 12-14 in Building D were not included due to data unavailability.

We used three data sources: 1) records of site cameras, 2) installation records by subcontractors and 3) discussions with site personnel. We did not use the master plans updated by planners due to their low accuracy. This is because progress was updated about once a week and had many inconsistencies compared to site camera records and other sources.

ANALYSING THE DATA

Unlike in manufacturing, where a product is a discrete entity, in construction, a location can be defined to have any size. The projects used in this research did not use location-based scheduling. Hence, there were no predefined location breakdown structures. However, each level in a building had a general sequence of slab concrete pours, and the crews usually worked in that sequence. Therefore, a location was defined as the building area corresponding to a major slab pour. Accordingly, process and operations flow metrics were calculated, and IBM SPSS 28 was used to conduct correlation and regression analyses between the variables defined earlier.

RESULTS

There were 86 locations and 19 crews across the four buildings. Figure 3 presents their flowline charts. Buildings A and B belong to the same project, and the subcontractor used a single steel fixer crew for both buildings. The time spent by the crew in the other building is shaded. It corresponds to Portfolio flow as defined in Sacks (2016), which represents the workflow from project to project (in our case, from building to building). The flowlines in Buildings C and D are arranged closer together and seem to have relatively smooth flows with fewer breaks. Conversely, Building B has the worst flow quality, with flowlines spaced apart.

CORRELATION ANALYSIS

Tables 3 and 4 present the results of the linear correlation analysis of process and operations flow metrics. The four flowline charts show that slab concreting usually takes only a day in each location. This is an outlier when analysing process flow metrics. Hence, it was not included in the calculations for the mean and variability of location production rates. Note that adjustments were also made for holidays and weekend working hours.

REGRESSION ANALYSIS

Multiple linear regression of the process flow metrics yields Equation 1 for the overall location production rate. This model has an R^2 value of 0.72. Similarly, the multiple linear regression of the operations flow metrics yields Equation 2 for the overall trade production rate. This model has an R^2 value of 0.52. The variance inflation factor of each independent variable was much less than 5, indicating a low multicollinearity level.

Overall Location Production Rate =
- 224.96*Excess WIP time - 8.41*Variability of Location Production Rates

+ 0.10*Mean Location Production Rate + 26.15 Equation 1

Overall Trade Production Rate = - 3756.20*Proportion of Breaks + 117.09 Equation 2

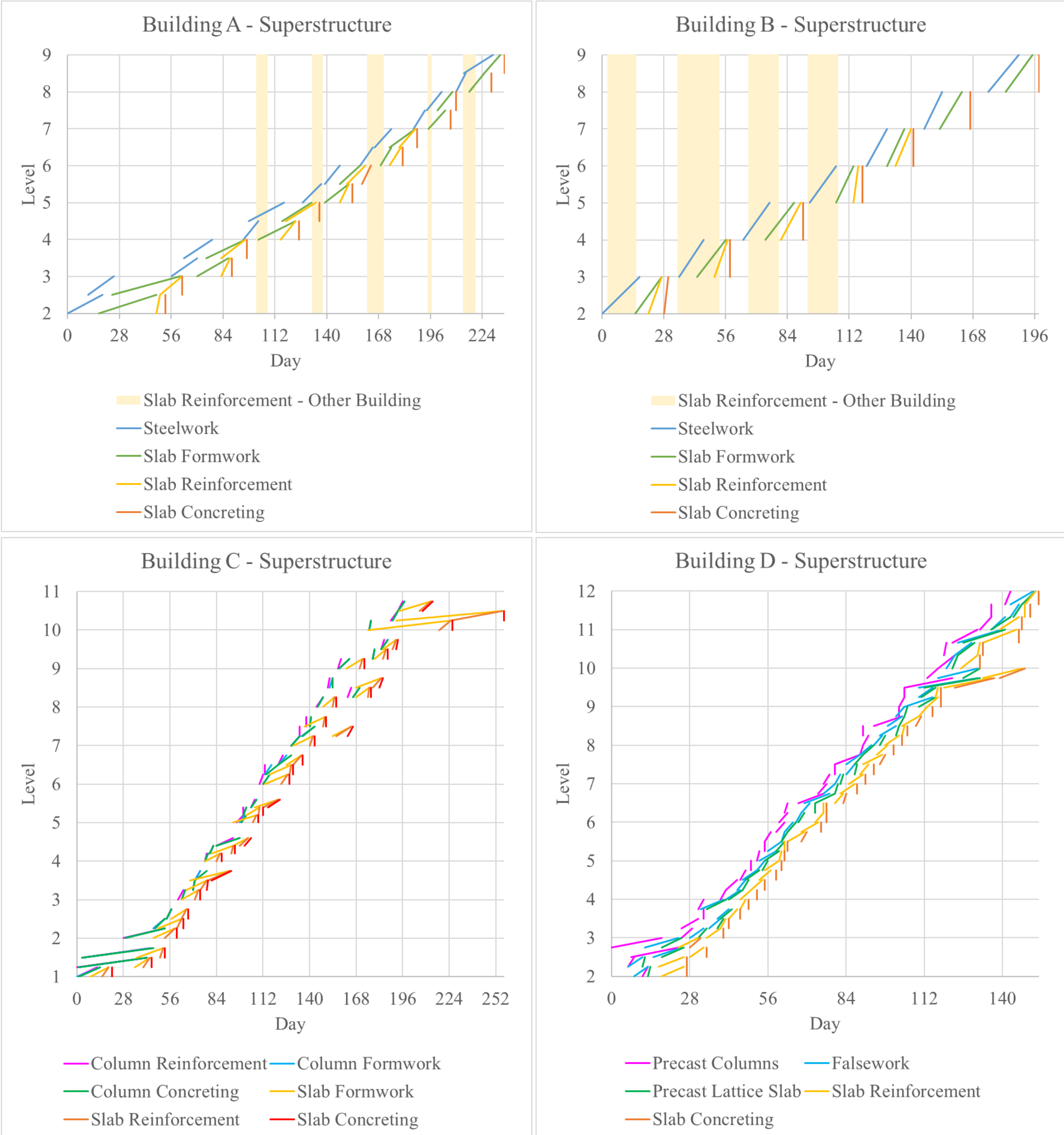

Figure 3: Flowline Charts of Building A, B, C and D Superstructure

Table 3: Correlation Results of Location Productivity with Process Flow Metrics ($p<0.01$)

Metric	Pearson Correlation Coefficient (r)	Coefficient of Determination (R^2)	Correlation Category
Excess work-in-progress time	-0.75	0.57	Strong negative
Mean location production rate	0.59	0.34	Moderate positive
Average batch size	-0.49	0.24	Moderate negative
Variability of location production rates	-0.35	0.12	Weak negative

Table 4: Correlation Results of Trade Productivity with Operations Flow Metrics ($p<0.01$)

Metric	Pearson Correlation Coefficient (r)	Coefficient of Determination (R^2)	Correlation Category
Level of work discontinuity	-0.72	0.52	Strong negative
Mean trade production rate	Not significant	-	
Variability of trade production rates	Not significant	-	

EXPLANATION OF RESULTS

Tables 5 and 6 explain the results of metrics with a relatively high degree of correlation. The regression results are explained for two hypothetical cases: a 300 m^2 location with 5 crews for process flow and a 10,000 m^2 building with 20 locations for operations flow. The average batch size is not considered as it does not appear in the regression equation, even though it has a significant linear correlation with location productivity. This might be because it does not bring additional significant information to the model. It has a moderate linear correlation of 0.56 ($p<0.01$) with the excess work-in-progress time showing similar effects on location productivity.

Table 5: Explanation of Process Flow Results

Metric	Correlation Analysis	Regression Analysis (for a 300 m^2 location with 5 crews)
Excess work-in-progress time	If the gaps between the start dates of successive activities at a location are reduced, there is a strong chance that the location's production rate will be increased.	If each of the five crews can start one day early, the overall location production rate will increase by about 4 m^2/day.
Mean location production rate	If the mean production rate of each crew at a location is increased, there is a moderate chance that the location's production rate will be increased.	If each crew can improve their production rate by 1 m^2/day, the overall location production rate will increase by about 0.1 m^2/day.

Table 6: Explanation of the Operations Flow Results

Metric	Correlation Analysis	Regression Analysis (for a 10,000 m^2 building with 20 locations)
Level of work discontinuity	If a crew can reduce the non-working period between different locations, there is a strong chance that the crew's production rate will be increased.	If a crew starts each of the 20 locations one day earlier, the overall trade production rate will increase by about 7 m^2/day.

FACTORS THAT AFFECT CONSTRUCTION FLOW

We identified several aspects of construction flow that can be improved to increase overall productivity. The question now is what factors affect construction flow. We explored one such factor: the number of locations per floor in a building. We compared the slab reinforcement and slab concreting activities which are common to the four buildings.

Buildings B, A, C and D had an average of 1, 2, 3 and 4 locations per level. In these four buildings, the slab reinforcement crews spent approximately 77%, 61%, 34% and 14% of the total days onsite without work due to the unavailability of a location to conduct work. Similarly, the slab concreting crews spent approximately 94%, 90%, 57% and 53% of their total days without work. This shows a direct inverse relationship between the number of locations per level and the level of work discontinuity. Dividing large slabs into many smaller locations can help ensure the availability of work for the crews.

This issue also has productivity implications. Site attendance records reveal that the crews were present almost every day. Still, when work was unavailable due to the unavailability of a location, they were allocated to support tasks such as cleaning and moving materials. This results in the underutilisation of skilled workers who are paid higher salaries, which is a productivity loss. We expect to uncover similar factors affecting construction flow in the future, e.g. the effect of having offsite components.

DISCUSSION

OPTIMUM SIZE OF A LOCATION

The results show that having less excess work-in-progress time, i.e. reducing the gaps between the start dates of successive activities, significantly impacts overall productivity. As mentioned earlier, having less work-in-progress is a feature of a good construction flow. Therefore, it is understandable that it leads to better productivity. However, according to the flowline charts (Figure 3), there are many locations where activities started before ending the previous activities. The results lead us to believe that having more than one crew working simultaneously at a location can improve productivity. But previous studies show that this can lead to congestion and, ultimately, low productivity (Kenley & Seppänen, 2010). The underlying issue is that all the projects in this study used traditional scheduling methods, such as Gantt charts, based on critical path techniques instead of location-based methods. There were no predefined location breakdown structures, and the locations' sizes varied across building levels and with time. Also, the planned location sizes of the buildings were too large. The average location size of buildings A, B, C and D were 626, 655, 311 and 403 m^2, respectively. These were too large for the crews who, on average, had only 4-5 workers. With these location sizes, it is possible for two or even three teams to work in different areas of a location without leading to congestion. Hence, the correlation and regression results hold. However, the goal should be to have a higher number of small locations. Using location-based scheduling could have achieved that. Murguia et al., (2023) present a more detailed analysis of this topic.

MEAN AND VARIABILITY OF PRODUCTION RATES

According to operations flow results, ensuring continuity of work or resource use strongly improves trade productivity. However, surprisingly, the results show that trade productivity is not significantly affected by the mean or variability of crew production rates at different locations. From a flowline perspective, it means that productivity is more influenced by the gaps between the flowlines and not by their gradient or the variation of the gradient. Hence, in actual projects, there is a significant opportunity to improve project performance by better dividing/sequencing the activities than by having crews work faster or more consistently. Note that the size of the dataset limits operations flow results. We are working on collecting more data to solidify these findings.

Synchronising production rates of different crews is an important step of location-based scheduling (Kenley & Seppänen, 2010). Yet, process flow results show that variability of location production rates only has a small effect on location productivity. The results might be because trade production rates (except for slab concreting) are already reasonably synchronised in the projects (see the flowlines in Figure 3). Both these results show the benefits of using actual project data for the analysis, as opposed to planned or simulated data. Our results show the construction flow issues that real projects must address to improve performance.

OTHER FACTORS AFFECTING CONSTRUCTION PRODUCTIVITY

The two linear regression equations developed have R^2 values of 0.72 and 0.52. This means the developed metrics explain 72% and 52% of the variation in location and trade productivity. There are other factors that may not be directly linked to flow-related metrics. For example, when using flowlines, we assume that crews work continuously in a location during the period denoted by a flowline before moving on to the following location. In reality, workers may not fully utilise their time due to different reasons. Moreover, some projects in our analysis used offsite components such as precast columns and composite beams. They could have also led to differences in productivity. Rathnayake and Middleton (2023) presented a review of various such factors that affect productivity. A complete model for construction productivity should include factors that are both related and unrelated to flow. Finally, construction productivity is a combination of location and trade productivity. In the future, we will explore how much each flow type can impact overall project productivity.

CONCLUSIONS

This study aimed to identify what aspects of construction flow affect productivity and quantify this impact. There are two main types of construction flow: 1) process flow, which represents the flow of activities performed at a single location and 2) operations flow, which represents the activities performed by a single trade through different locations. Using literature, we developed a set of metrics to describe these two types of flow. Then, we used the data relating to the superstructure construction of four buildings to measure these metrics. Their impact on productivity was quantified through correlation and regression analyses. The process flow was compared with the productivity of individual locations, and the operations flow was compared with the productivity of separate crews.

Four process flow metrics, excess work-in-progress time, mean location production rate, average batch size and the variability of location production rates, were found to have strong negative, moderately positive, moderately negative and weak negative linear correlations with location productivity, respectively. The linear regression equation developed using these factors explained up to 72% of the variation in location productivity. One operations flow metric, the level of work discontinuity, was found to have a strong negative relationship with trade productivity, with the former explaining up to 52% of the variation in overall crew productivity.

We found that the sizes of the locations used by the projects were too large when compared to the crew sizes. This meant that productivity could be improved by having multiple crews working simultaneously at a location. However, for better efficiency, work should be planned in smaller locations using a technique such as location-based scheduling.

This study presents initial evidence of the potential improvements in performance achievable by focusing on construction flow. We are working on strengthening the current dataset to solidify these findings. In the future, we expect to expand these findings to cover other work packages and other aspects of flow.

ACKNOWLEDGEMENTS

We would like to thank our industry partners for entrusting us with actual construction data and their continued engagement with this research project.

REFERENCES

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M. J., Sridhar, M., Parsons, M., Bertram, N., & Brown, S. (2017). *Reinventing construction: A route to higher productivity*. McKinsey Global Institute. https://www.mckinsey.com/capabilities/operations/our-insights/reinventing-construction-through-a-productivity-revolution

Bertelsen, S., Henrich, G., Koskela, L., & Rooke, J. (2007). Construction Physics. In C. L. Pasquire & P. Tzortzopoulos (Eds.), *15th Annual Conference of the International Group for Lean Construction* (pp. 13–26). https://www.iglc.net/Papers/Details/453

Frandson, A., Berghede, K., & Tommelein, I. D. (2014). Takt-Time Planning and the Last Planner. In B. T. Kalsaas, L. Koskela, & T. A. Saurin (Eds.), *22nd Annual Conference of the International Group for Lean Construction* (pp. 571–580). https://iglc.net/papers/Details/1063

Hopp, W. J., & Spearman, M. L. (2011). *Factory Physics* (3rd ed.). Waveland Press, Inc.

Kalsaas, B. T., & Bolviken, T. (2010). The Flow of Work in Construction: A Conceptual Discussion. In K. Walsh & T. Alves (Eds.), *18th Annual Conference of the International Group for Lean Construction* (pp. 52–62). https://www.iglc.net/Papers/Details/718

Kenley, R., & Seppänen, O. (2010). *Location-Based Management for Construction: Planning, Scheduling and Control*. Spon Press.

Koskela, L. (1992). *Application of the new production philosophy to construction* (CIFE Technical Report No. 72). Stanford University. https://stacks.stanford.edu/file/druid:kh328xt3298/TR072.pdf

Little, J. D. C., & Graves, S. C. (2008). Little's Law. In D. Chhajed & T. J. Lowe (Eds.), *Building Intuition: Insights From Basic Operations Management Models and Principles* (pp. 81–100). Springer US. https://doi.org/10.1007/978-0-387-73699-0_5

Murguia, D., Rathnayake, A. & Middleton, C. (2023). Master schedule optimisation with the use of flowlines and performance data. Proceedings of the 31st Annual Conference of the International Group for Lean Construction (IGLC31), 1463–1474. https://doi.org/10.24928/2023/0121

Olivieri, H., Seppänen, O., Alves, T. da C., Scala, N. M., Schiavone, V., Liu, M., & Granja, A. D. (2019). Survey comparing critical path method, last planner system, and location-based techniques. *Journal of Construction Engineering and Management*, *145*(12), 04019077. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001644

ONS (Office for National Statistics). (2023). *Output per hour worked, UK* [Data set]. ONS. https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/datasets/outputperhourworkeduk

Rathnayake, A., & Middleton, C. (2023). Systematic Review of the Literature on Construction Productivity. *Journal of Construction Engineering and Management*, *149*(6), 03123005. https://doi.org/10.1061/JCEMD4.COENG-13045

Sacks, R. (2016). What constitutes good production flow in construction? *Construction Management and Economics*, *34*(9), 641–656. https://doi.org/10.1080/01446193.2016.1200733

Sacks, R., Seppänen, O., Priven, V., & Savosnick, J. (2017). Construction flow index: A metric of production flow quality in construction. *Construction Management and Economics*, *35*(1–2), 45–63. https://doi.org/10.1080/01446193.2016.1274417

Seppänen, O., & Kankainen, J. (2004). Empirical research on deviations in production and current state of project control. In S. Bertelsen & C. T. Formoso (Eds.), *12th Annual Conference of the International Group for Lean Construction*. https://iglc.net/Papers/Details/330

Shingo, S. (1989). *A study of the Toyota production system: From an Industrial Engineering Viewpoint* (A. P. Dillon, Trans.; Revised Edition). Productivity Press.

Tommelein, I. D., Singh, V. V., Coelho, R. V., & Lehtovaara, J. (2022). So Many Flows! In F. Hamzeh & T. Alves (Eds.), *30th Annual Conference of the International Group for Lean Construction* (pp. 878–889). https://iglc.net/Papers/Details/2015

Walsh, K. D., Sawhney, A., & Bashford, H. H. (2007). Production equations for unsteady-state construction processes. *Journal of Construction Engineering and Management*, *133*(3), 254–261. https://doi.org/10.1061/(ASCE)0733-9364(2007)133:3(254)