Asmone, A.S., Murguia, D., Rathnayake, A. & Middleton, C. (2024). Automated Data Capture and Analysis to Detect Process Waste in Interior Finishing Work. In D. B. Costa, F. Drevland & L. Florez-Perez (Eds.), *Proceedings of the 32nd Annual Conference of the International Group for Lean Construction* (IGLC32) (pp. 660–671). doi.org/10.24928/2024/0135

AUTOMATED DATA CAPTURE AND ANALYSIS TO DETECT PROCESS WASTE IN INTERIOR FINISHING WORK

Ashan Senel Asmone[1], Danny Murguia[2], Asitha Rathnayake[3] and Campbell Middleton[4]

ABSTRACT

Detecting process waste in complex production systems is still a challenge in construction projects. The integration of lean construction with automated data capturing technologies presents an opportunity to timely detect process waste and steer projects towards targets. By using vision-based technology for automated progress monitoring in a residential building, this study examines interior finishing work activities through the lenses of process/location flow and operations/trade flow. Location-based management tools (flowlines and line-of-balance) were used to visualise the data. Results showed that planned production deviated from actuals in all activities. Significant variability was observed within the completion of each activity at each location. The ratio between average production rate and exemplar performance indicated a missed opportunity to improve project performance. Resultantly, several waste types were identified including inefficient work, space not being worked in, unnecessary movement of people and unnecessary transportation of materials. The ability to actively pinpoint process waste provides managers with a granular understanding of inefficiencies, enabling targeted interventions to enhance productivity and reduce waste. The findings support that automated data capturing and analytics through the lenses of lean construction is a useful strategy to inform construction programmes to be more realistic, improving upon efficiency and waste reduction.

KEYWORDS

Flow, process, waste, location-based management (LBM), work in progress/process (WIP).

BACKGROUND

Waste is defined as the use of more resources than needed to generate an output, or the production of an unwanted output (Bølviken et al., 2014). According to Bølviken and Koskela (2016), the industry's significant waste is primarily attributed to the management approach in construction, which often prioritises contract management over production management. Additionally, this issue is exacerbated by the complexity of construction with multiple tiers of subcontractors and low-price procurement strategies. Bølviken et al., (2014) defined flow waste in construction as 1) unnecessary movement (of people); 2) unnecessary work; 3) inefficient

[1] Research Associate, Department of Engineering, University of Cambridge, UK, asa79@cam.ac.uk, orcid.org/0000-0002-2173-3890

[2] Senior Research Associate, Department of Engineering, University of Cambridge, UK, dem52@cam.ac.uk, orcid.org/0000-0003-1009-4058

[3] PhD Candidate, Department of Engineering, University of Cambridge, UK, agbrr2@cam.ac.uk, orcid.org/0000-0002-1389-7801

[4] Professor, Department of Engineering, University of Cambridge, UK, prof@construction.cam.ac.uk, orcid.org/0000-0002-9672-0680

work; 4) workers waiting for work to be done; 5) space not being worked in; 6) materials not being processed; 7) unnecessary transportation (of materials).

Interior finishing work package is challenging due to the presence of multiple subcontractors, lack of detailed planning and control, and the complex linkages between tasks. Previous research has found high levels of work-in-progress (WIP), long cycle times, and significant process waste during this work package. Brodetskaia et al. (2011) found that subcontractor capacity unpredictability causes turbulent workflow, and re-entrant workflow patterns, in which crews return to the locations multiple times affecting performance. Murguia et al. (2016) applied the Value Stream Mapping (VSM) tool to detect process waste in interior finishing work and implemented a new work structuring, collaborative planning, and the flowline method to reduce cycle times. Due to the inherent complexity of this work package, it is difficult to determine which areas are performing optimally and which areas need improving.

To make visible and eliminate waste, a constant stream of production data generated in the field needs to be observed and analysed. However, project teams do not have the ability nor the bandwidth to collect this data whilst managing other aspects of construction. Therefore, a focus on production management along with automated data capture and analysis becomes a real need in order to identify areas where project teams should direct their efforts to avoid cascading delays. Technologies such as laser scanning (Wei et al., 2018), video data, computer vision, (Khosrowpour et al., 2014; Roberts et al., 2020; Görsch et al., 2022), and sensors (Akhavian & Behzadan, 2016; Barbosa & Costa, 2021) are used for this. Automated progress monitoring in construction involves capturing as-built data from sites and estimating progress by comparison with plans. One commonly used method for data collection is handheld 360-degree cameras (Ekanayake et al., 2021; Sami Ur Rehman et al., 2022).

By analysing internal processes and performance on the ground, it can be used to detect waste and see where efficiency optimisation is possible. To that end, the objectives of this paper are 1) to detect process waste in interior finishing work using vision-based automated data capture and 2) to describe the current challenges of vision-based data capture technology.

RESEARCH METHOD

A case study approach was used in this research to observe interior finishing work activities at a residential building development in London. Data collected included the construction programme and progress data. The construction programme was used to create the baseline to compare plans and actuals. The progress data were collected at weekly intervals using a 360^0 camera. A construction technology company provided services for this project to automatically analyse visual data using advanced computer vision techniques and record progress. The research team had access to the data via an online system including date of capture, 360^0 images, location (i.e., apartment), trade, activity, and percentage of cumulative progress.

However, our approach relied on investigating progress between two consecutive measurements (i.e., quantity of work carried out at a certain time interval) to better understand the flow of activities at each location. As such, flowline charts and line-of-balance (LoB) diagrams were used to visualise operation/trade flows and process/location flows. LoB diagrams have two visual representations, with some authors using dual parallel lines to represent activities, whereas others use boxes (Tzortzopoulos et al., 2020). In this paper, the second method was used. A data-to-dashboard approach (Murguia et al., 2022) was used to generate LoB visualisations automatically using Python codes purposively created for this research. With the data, the following metrics were calculated: 1) actual duration, 2) average cycle time, 3) average days worked, 4) number of visits to location, 5) production rate, and 6) observed exemplar and worst performance. These metrics have been proposed in previous studies (Rathnayake et al, 2023). We used these diagrams and metrics to visualise and quantify different types of waste at each unit location (i.e., apartment).

RESULTS

The case study was a residential building project constructed on a design and build contract. The internal fit-out activities were sub-contracted. Five fit-out activities in the critical path of the construction programme were observed, viz. erecting demising walls, internal wall closure, ceiling closure, painting, and flooring. For this study, observations and analysis were limited to a single level (level 4) which included ten apartments in total. A 360^0 camera was used to capture the weekly progress of interior finishing work. Cumulative progress was determined using a computer vision-based algorithm. The deployment of this technology was a pilot project within the business. Planners and site managers were unfamiliar with the potential to use the data to inform decisions. Traditional Gantt charts and activity counts were used as control metrics in measuring progress. Progress data were unused in production management.

PLAN AND ACTUALS

Data drawn from the online system were used to generate flowlines for the fit-out activities in level 4 (Figure 1). The horizontal axis shows calendar dates whilst the vertical axis shows the locations (apartments 401 through 410). An examination of the flowlines provides some understanding of actual performance. First, the flowlines indicated a clear mismatch between planned and actual progress. About 1/4th of the activities finished before their planned completion, while the rest of the activities were delayed, averaging a fourfold delay over their planned durations. Second, sequence deviations were observed between activities. For instance, flooring activities commenced in apartment 7 before painting even though the plan indicated a finish-to-start relationship between the two activities. This attests to the complexity of the interior finishing work package in managing several activities among several trades. Third, plans were made with the "level" (e.g., level 4) as the smallest unit as opposed to the "apartment". For instance, all the demising walls and internal wall closures were planned simultaneously across the ten apartments. However, granular data at the apartment level were available from the online system. Notwithstanding the above, the time lag between data collection made it impossible to differentiate the exact installation dates at each location. For instance, all demising walls for apartments 403 to 406 were installed between January 15th and January 29th. Therefore, the flowlines (in red) for these were identical across locations. Finally, the flowlines' slopes vary significantly between different locations suggesting different production rates. For instance, the production rates for internal wall closures (in blue) for apartments 401 to 404 were significantly different to those of apartments 405 to 410. Therefore, further analysis is needed to understand the differences and LoB diagrams were used to explore how much work was accomplished over time at each location (see Figure 2).

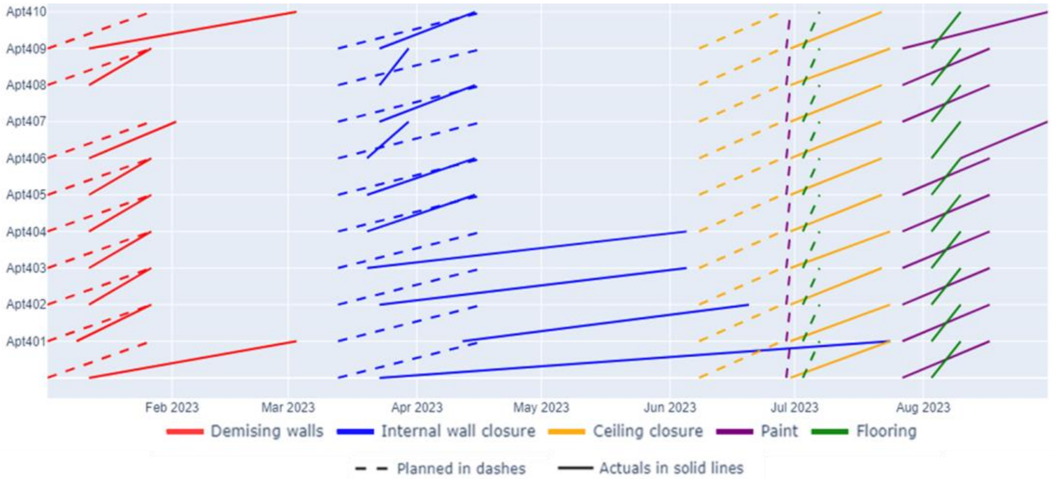

Figure 1: Flowlines – planned v actual

OPERATION/TRADE FLOW

In construction, products are stationary, and workers and equipment move across locations. Therefore, the two types of flow can be redefined as follows: 1) process/location flow, where different trades flow through a single location, and operations/trade flow, where a single trade flows through different locations (Sacks, 2016; Tommelein et al., 2022). Figure 2 shows the LoB diagrams for the five activities under examination across the ten locations. The horizontal axis indicates calendar dates, and the vertical axis indicates each location. The faint vertical bars in the background indicate weekends and public holidays. Each LoB illustrates one or more segments along the activity duration. Each segment is defined by two consecutive data capture events. The colour of each segment indicates the percentage of average daily work done during that period (i.e., % of progress/number of days, the corresponding colours can be found in the legend). Segments with no colour mean no work done.

Figure 2: Line-of-balance – operation/trade analysis

Each LoB diagram illustrates when work started, % of average daily progress between observations, revisits to the same location, and notably, when the locations were left idle with no area utilisation. However, a manual cross-check with site images showed that in many apartments the work was completed without any idle time as suggested by the data. In the case of painting, further investigations showed the separate work done earlier couldn't have been avoided due to the interdependencies of different activities. Managing this has to do not only the trade delivery monitoring but also with better planning the sub-activities. LoB diagrams are a handy way to visualise not only the progress of each activity over time but also the different types of process waste occurring at each location. As mentioned, area utilisation is clearly observed in the LoB diagrams, and so are sequence deviations from plans, as well as the distribution of a single trade over different areas of a level. An additional layer of information provided in these diagrams is the colour intensity indicating the rate of work done. This illustrates a variance between work done over different observed periods. For example, for apartment 1 ceiling closure, 47% of the work was done in 1 day and the rest over 16 days.

However, the LoB diagrams in Figure 2 only show one part of the story. As in the fit-out phase multiple trades are operating in close proximity to one another within a short period of time it is equally important to see how the different activities progress over time at a single location. Hence, LoB diagrams were drawn illustrating each apartment (see Figure 3).

PROCESS/LOCATION FLOW

Figure 3 shows a location analysis of a sample of three apartments. The LoB diagrams visually depict a number of process waste occurring at each location, viz. idle time, revisits, sequence deviations, and output inconsistencies (indicated by the varying colours of the boxes). Moreover, this visual prompt allows digging deeper into area utilisation at each apartment. The results show that apartment 401 took 156 net working days to complete the observed interior finishing work package activities from the first start to the last finish of an activity. However, it was only on 59 working days that an actual activity was carried out by at least one trade at this location, indicating an area utilization of 38%. This example indicates a common theme of wanton waste occurring during this construction phase, waste that can be easily identified using the right analytical tools to be dealt with by project teams to optimise their performance. However, it also is indicative of an underlying limitation of automated data capturing, where other uncaptured activities may be happening in these locations.

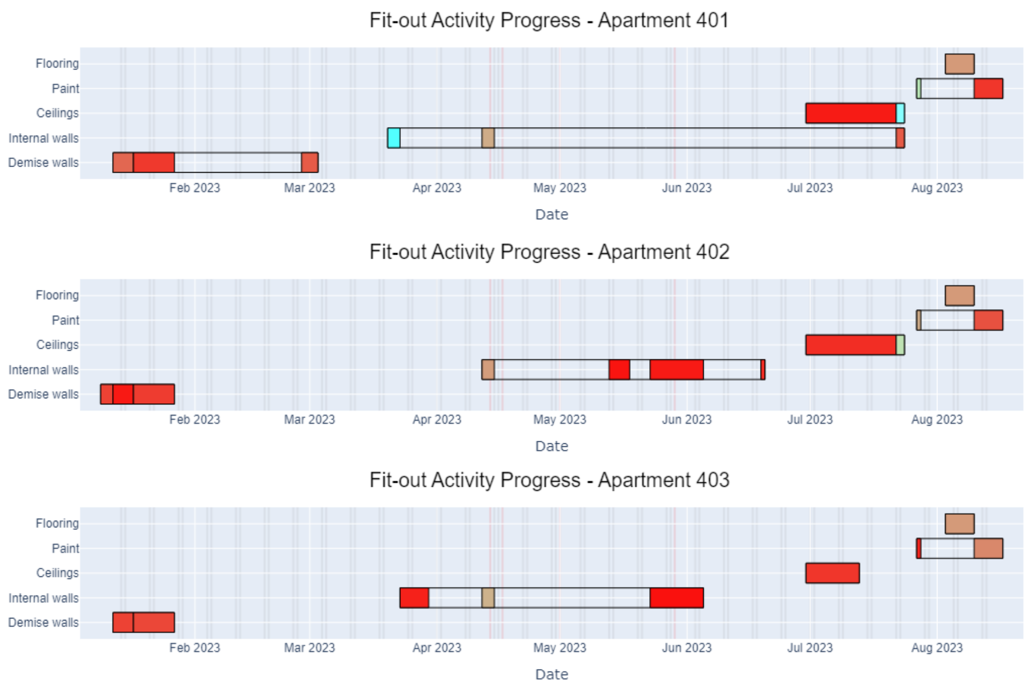

Figure 3: Line-of-balance – process/location analysis

To further explore process flow within locations, the research team analysed image data to obtain the actual start and end dates for all activities at a given location, as depicted in Figure 4. This figure introduces a novel flowline visualisation, showcasing activities on the Y-axis rather than locations, beginning from "demise walls" to "carpentry & joinery." The sequence of activities and their planned dates were extracted from the project Gantt charts and are depicted in blue. The actual data (in red) were derived from visual examination of the image data. Focusing on a specific location, level 4 – apartment 5, a notable gap between plans and actuals was observed in most activities. Notably, despite the first activity commencing earlier than planned, a substantial gap between the completion of demising walls and the initiation of MEP

1st fix was evident, indicating considerable work in progress (i.e. space not being worked in). Similarly, a gap exceeding one month was identified between the completion of internal walls and the start of MEP 2nd fix. Moreover, the production rate of MEP 2nd fix was significantly lower than the plan, as evidenced by the extended duration of the activity. The visual comparison between planned and actual start and end dates provide a clearer picture of progress. Whilst these analysis was conducted retrospectively, the tool and visualisation technique can be applied on future projects to monitor progress across locations (apartments, levels, buildings), enhance situational awareness, improve decision-making, and generate data for future projects.

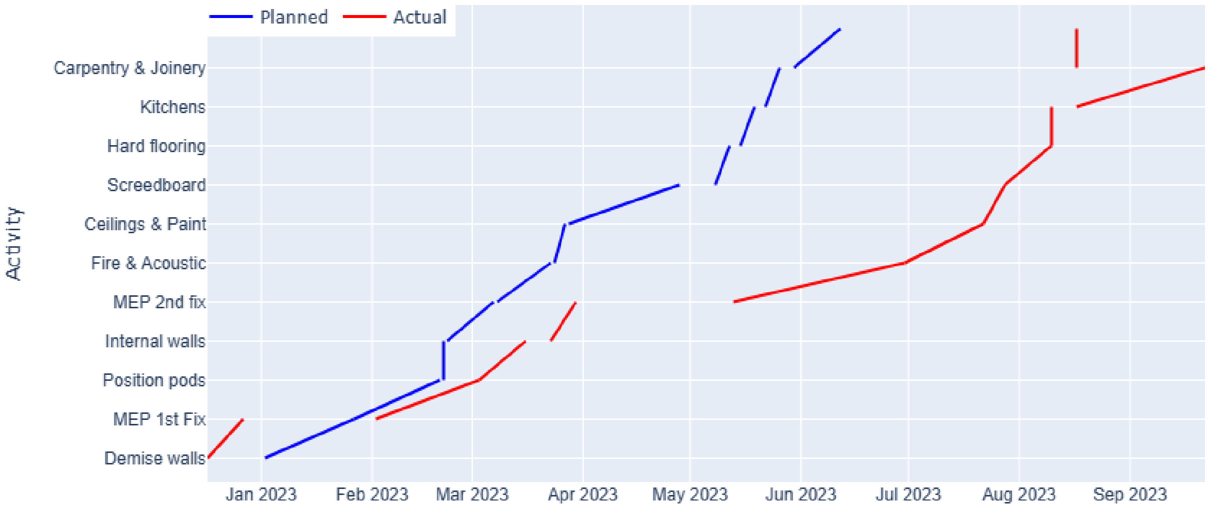

Figure 4: Process flow – example of level 4 apartment 5

METRICS

Table 1 provides some metrics on activity durations at the smallest location unit considered in this study, the apartments. As mentioned earlier, the Gantt Charts plans dictate fit-out activities at each apartment to be carried out simultaneously, yet evidence shows that there is significant variability between the time taken to complete activities in each apartment. For example, considering the activity of internal wall closure, that activity has a large variability in its overall completion times. However, looking closely at why that is the case it was observed that this activity has some sub-activities (e.g., drywall lining, single and double-sided partitioning) that were dependent on work completion by various other trades (e.g., demise wall, pipework, bathrooms, kitchen). Therefore, this trade could not complete their work at certain locations as per their schedule. The quantities of work conducted do vary between the different apartments, although that difference is not significant. These results are indicative of output inconsistencies.

The metrics of average cycle time and average days worked at an apartment are useful in terms of understanding process waste observed at the site. Both are measures of waste and are indicative of the mismatch between planned and actual realisation of plans, thus leading to waste. Apart from flooring activity, all other activities have varying average cycle times and days worked. With a variability of over 5 times with the planned duration in the case of painting. This type of metrics can be fed back to the planning process to make plans more realistic.

Table 1 further shows the number of visits from each trade to a single apartment to complete the activities during this duration. This was also observed in Figure 3. It is observed that while some activities are carried out from start to finish during one visit to the location, in many cases multiple visits are made to the same location over time to complete the same. Indicating idle time at these locations. Among the insights this shows, the distribution of a single trade over different areas of a level can be important information to the construction managers on site. Output inconsistencies at each location within level 4 are further collated in Table 2.

A summary of production rates for each activity is given for each location (i.e., apartment) and time interval (i.e., between two observations). In this study production rate is defined as the ratio of output to time. The output inconsistencies are observed to a greater degree when considering the varying production rates for both categories, location-wise and time interval-wise. In the example of ceiling works, the production rate ranges from 2.2 m/day to 16.4 m/day at different apartments. At the same time, in between the different observations made over the weeks when work is carried out an exemplar rate of production can be established at 6.43 m/day. On the other hand, the worst performance for this trade indicated a measly 0.01 m/day during a separate time. Interestingly, when analysing the complete results over time at each location, no inferences can be made from this data only to explain this behaviour of varying production rates. From the current observations, it is seen that high production rates are achieved at one location at the beginning of the work, and they fall off over time, yet the opposite happens at a different location. The only conclusion that can be made from the present data is that there is no consistency in the production rates. There may be several contributing factors explaining this variability. Further contextual data must be provided to determine these factors.

Table 1: Descriptions for observed fit-out activities (Level 4)

Activity (Trade)	Planned duration (days)	Actual duration (days)	Duration per location (apartment) (days)				Visits to location (apartment)	
			Minimum	Maximum	Average cycle time	Average days worked	Minimum visits	Maximum visits
Demise walls	20	53	17	34	21.3	16.4	1	3
Internal walls	26	126	8	30	17.3	13.1	1	2
Ceilings	15	24	23	24	24.2	16.4	1	1
Paint	2	35	10	35	12.8	10	1	1
Flooring	5	7	7	7	7	6	1	1

Table 2: Production rate metrics for observed fit-out activities (Level 4)

Activity	Production rate (m2/day)			Per time interval	
	Overall average per location	Minimum per location	Maximum per location	Observed exemplar	Observed worst
Demise walls	2.5	0.5	6.2	15.9	0.07
Internal walls	1.9	0.5	6.4	13.8	0.04
Ceilings	5.4	2.2	16.4	9.6	0.03
Paint	10.0	1.8	22.9	29.8	0.29
Flooring	21.9	21.9	21.9	5.52	5.52

The statistical inferences supplement the visual diagrams developed when informing the project teams of the interior finishing work packages. They are used to provide additional clarity, offering a comprehensive view of the sequence and interdependencies of various tasks within the interior finishing work packages. In tandem, these provide a more intuitive and accessible means for project teams to understand the temporal relationships between tasks, identify potential bottlenecks, and process waste to prompt optimised resource allocation.

DISCUSSION

This paper aimed to detect process waste in interior finishing work using automated data capture and analysis. The findings presented above show several inconsistencies between planned and actual work. This section discusses how the observed findings relate to the different types of process waste established in the lean construction literature.

According to Navon and Sacks (2007), project teams waste considerable time due to poor coordination, inaccurate and late information. If the work at a location is completed earlier than scheduled it results in early completion of activities, with waste of work efforts resulting in WIP at said location until the next trade moves following the schedule. This waste was observed in the data due to high variability in actual production duration in locations by many different trades. Relatedly, WIP (i.e., space not being worked in) as waste is noted throughout the observed period as locations are kept idle for long stretches of days in certain instances. For example, Table 1 shows the duration per location for each activity, indicating variations in the time taken to complete tasks in different apartments. Idle time in this case can be attributed to the coordination between trades in the critical path as well as the speed of their production during active installation. The varying production rates for each activity are presented in Table 2. The observed fluctuations in production rates suggest inefficient work at certain locations, which is yet another process waste. The delays and discrepancies between planned and actual durations may indicate potential issues with delivering the final specified results at each location. This is considered an indication of production defects. However, further contextual data such as quality reports must be used to substantiate this, which was not part of the scope of this paper. However, this work supports to overcome the manual observation of construction activities to measure performance, which has clear merits (Roberts et al., 2020).

Other types of waste identified are related to the unnecessary transportation of material and unnecessary movement of people arising from multiple visits to the same location to complete an activity. With multiple visits to a single location, further transportation-related issues can occur such as poor logistic conditions due to material and equipment left behind by different trades at locations where they intend to return. The waste types relating to inventories were not explicitly observed from the data. However, an additional waste discussed in lean management literature, underutilisation of talent, can be inferred by looking at the present data. This is suggested by the varying production rates for different trades. Some locations exhibit high productivity initially but experience a decline over time, indicating the potential underutilisation of talent. The trades could have potentially achieved more productive work in locations, given any contributing blockers to productivity were identified and managed within a timely manner. Therein lies an opportunity for improvement (Gondo & Miura, 2020).

In this research, several metrics were used to identify construction process waste, as discussed above. These metrics themselves provide a foundational framework for automated data capture and analysis for project teams. Thus, aiding them to identify and address shortcomings within their projects in a timelier manner. The results provide evidence to support the practical implications of such metrics, particularly in identifying and addressing sequence deviations to avoid cascading effects on project schedules. This in turn would help optimise area utilization for faster turnaround times and maintain trade output consistency for more accurate timeline predictions whilst reducing return visits to locations. When integrated into construction project planning and management, the study results help close the empirical data loop between planners and the site conditions during interior finishing works. This provides a comprehensive understanding of project performance when combined with existing benchmarks such as schedule performance and other similar frameworks (Marcy et al., 2021).

Due to the inherent complexity of the industry, it is difficult to determine which areas of the project are performing optimally and which areas are improving. Location-based management is useful in navigating through various project information and identifying where efforts should be concentrated. By analysing internal processes and performance on the ground during interior finishing work, this study provides the framework to address coordination issues, improve planning, and enhance the flow of activities.

Automated data capture and analysis, therefore, provides a very clear opportunity to improve site activity level performance and productivity by removing each of the identified waste streams incrementally. More realistically this sort of analysis can be used to identify and empirically explain the notion that actual performance happens not along the best case as assumed by the plan. The planning fallacy, a bias marked by the underestimation of time, costs, and risks in future actions despite historical evidence, is at times used to explain these challenges (Love et al., 2019). This work provides a basis on which dynamic assessment of progress against initial plans can be facilitated automatically, which can potentially provide insights to combat the planning fallacy. Visual tools enhance comprehension, aiding project teams in identifying bottlenecks and adjusting plans (Arditi et al., 2022). Moreover, instant issue recognition and agile decision-making enable prompt responses to challenges, mitigating the rigid adherence to optimistic planning assumptions. This study proposes a data capture and analysis framework for optimising project resource allocation (see Figure 5), offering a data-driven approach to address inefficiencies and process waste. Therefore, this study helps identify the intersection between the gathered data and useful insights to update planning practices in interior finishing work. Practices which can be expanded throughout the construction industry with further work.

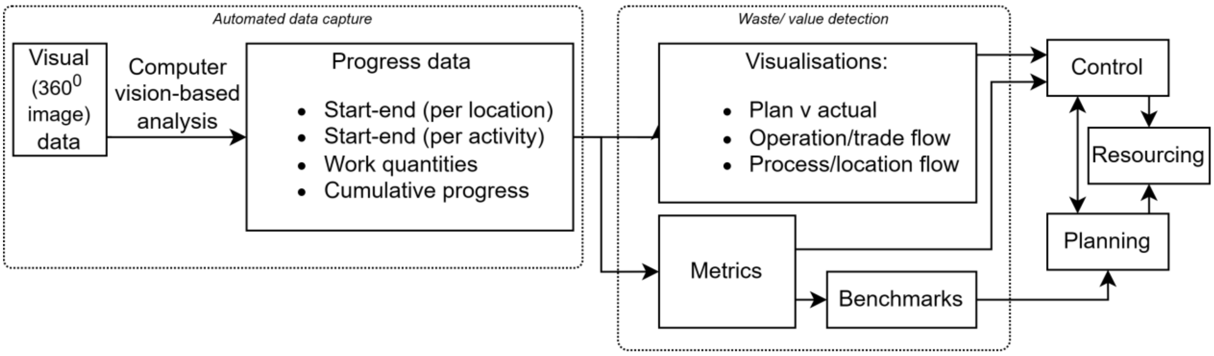

Figure 5: Automated data capture and analysis framework

CHALLENGES OF AUTOMATED DATA COLLECTION

Image data were captured on site at regular intervals and subsequently analysed using computer vision algorithms. However, upon analysing the resultant raw progress data, certain limitations were noted that need to be addressed to further advance the field. First, there were some discrepancies in the terminology and grouping of activities between the plans (Gantt Chart) and the actuals reported by the system. For instance, the plan had an activity named “Second drylining visit” whilst the system identified more granular activities such as “Frame”, “Closure”, and “Skim”. Whilst having this granularity is a strength of the system, it was unclear how to match the planned activities and the corresponding actuals for flowline creation.

Second, the system does not support the analysis of re-entrant workflows (Brodetskaia et al., 2011). For instance, the activity "Plumbing" groups several elements that were installed at different times. However, they were all consolidated into a single activity within the system. From a workflow perspective, it is essential to disaggregate these elements to understand the interactions with other activities.

The third limitation was due to some instances of errors in the start-end dates and progress calculation presented by the system. A manual quality check was carried out when durations were too long, and we found some differences between the images and the progress data generated. During the data processing and verification stages, these were corrected for the analysis to the best of the authors' ability. Although this research cannot report the rate of detection error, further work is needed to ensure more quality in the data.

The fourth shortcoming was due to the data collection intervals. In many cases, most activities within several apartments were completed between two consecutive observations. Consequently, all the flowlines are the same, despite trades potentially moving daily between apartments. Thus, production rates at the apartment level are meaningless unless they are aggregated at the floor level. In other instances, some activities in the critical path are not properly reported due to activities happening within the time elapsed between two consecutive observations (e.g., the placement of prefabricated bathroom pods in each apartment). Therefore, the weekly data collection frequency does not cater for measuring production at the operational level. A trade-off is needed between more frequent data collection and the level of analysis required. However, presenting the available data with a flow point of view as opposed to cumulative progress is a valuable contribution of this study.

Automated data capture provides an opportunity for planners to quickly capture an approximate measure of work done. It is envisaged that further advances in this technology would make the accuracy and reliability of data improve over time. Even so, in its current form, this technology along with a construction flow point of view can help planners close the loop between actual site performance with their plans for interior finishing work. It can show where deficiencies of plans may occur, or where additional time, resources, and methods are needed.

CONCLUSIONS

Underpinned by operations and process flow, this research investigates process waste by leveraging progress data extracted from image data collected during the interior finishing work of a residential building. Flowlines and line-of-balance were produced to enable improved situational awareness. Awareness that leads to targeted interventions. A key contribution of this research is the data capture and analysis framework that supports the identification and visualisation of various types of process waste, such as inefficient work, space not being worked in, unnecessary movement of people and unnecessary transportation of materials. Overall, the study explores the intersection between process waste and advances in automated site data generation, integrating Lean Construction with advanced digital technologies. The current work is limited in its use of a single case study. Albeit the research methodology presented in this study can be utilised for other construction work packages with identifying relevant metrics for each work package. Another limitation is the lack of qualitative data to contextualise and draw the causes for the observations. This form of data capture in its current form should not be used in isolation. This data should be used in conjunction with other site data streams such as quality reports, site diary entries, and planners' reports. Data captured automatically need contextual information to allow for understanding variations. The data collection is also limited to the level of granularity the work package plans are made. With more granular plans, the data could further be delved into sub-activities. To that end, this work succeeds in detecting process waste in interior finishing work using vision-based automated data capture and identifies the current challenges of vision-based data capture technology.

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