Digital Measurement of Construction Performance: Data-to-dashboard Strategy

Danny Murguia[1], Qian Chen[1], Tercia Jansen van Vuuren[1], Asitha Rathnayake[1], Vladimir Vilde[1] and Campbell Middleton[1]

[1] Laing O'Rourke Centre for Construction Engineering and Technology, Department of Engineering, University of Cambridge, 7a JJ Thomson Ave, CB3 0FA, UK

Corresponding author: dem52@cam.ac.uk

Abstract. Performance measurement in construction has been a topic of academic and industry inquiry in the UK since the 1990s. Despite the time elapsed, there is little evidence of a consistent industry-wide performance framework that drives decision-making and supports consistent measurement of performance on construction projects. A review of academic advancements and industry practices has been conducted to understand performance measurement in the construction industry, including the metrics assessed, processes for collecting and analysing data, and current limitations. The adoption of digital technologies on construction projects can support timely measurement of performance metrics, allowing for feedback and corrective action to improve performance. However, organisations struggle to connect the top-down measurement value with the bottom-up data capture technologies. The study of an exemplar commercial project was used to inductively develop a data-to-dashboard strategy that supports decision making in construction. The proposed strategy aligns performance metrics, digital tools and processes, and data analysis techniques in a consistent approach to interpret performance-related data and understand key issues. The development and review of the strategy on a live construction project highlights the challenges experienced with multi-source data integration and the translation of information into knowledge that drives decisions and deployment of timely corrective measures. The application of the strategy would ensure a consistent definition of metrics early in the project, and the continuous measurement of leading indicators. Future research will review the proposed strategy on further case study projects and develop an industry-wide multi-level performance measurement framework that uses the proposed strategy to improve performance.

1. Introduction

The construction sector suffers from many long-standing performance issues. Some of these include cost overruns, time delays, low quality, client dissatisfaction, low productivity, low profitability, cash flow-related issues, environmental issues and health and safety-related issues [1]. Effective management of performance issues requires an ongoing and strategic process that includes measuring performance and then a feedback system for analysis, reporting, and improvement [2]. Performance measurement has been defined as *"the process of quantifying the efficiency and effectiveness of actions"* [3]. As such, assessment of performance in construction can be conducted at varying levels: from task or activity, to work package, overall project, sub-sector and then at the highest level, overall sector performance to inform project, corporate, and policy decisions.

Performance measurement in the construction industry is highly variable and suffers from a lack of consistency in terms of what is measured as well as how [4]. During the construction phase, reliable, accurate information drawn from real-time project data is critical for supporting decision-making on construction projects and assessing that the performance is progressing as intended (and meets client/project teams' expectations). However, anecdotal evidence suggests that the plethora of digital technologies adopted on construction projects by organisations generate vast quantities of data that overwhelm organisations' abilities to integrate, evaluate and transform it into meaningful insights. This is exacerbated when the project team's approach to technology deployment and data analysis does not follow a clear needs-based process for generating insights that inform project decisions. As a result, there is a lack of clarity and consistency about what information and insights are needed from construction sites. Additionally, 'performance' and 'productivity' are often used interchangeably, an error that is likely due to the sector's historic focus on performance measurement using factors related to efficiency, effectiveness, and growth [2]. Current debates acknowledge the importance of improving long-term performance outcomes as the core goal for the construction sector [5]. However, in practice, performance measurement at all levels in the construction industry varies considerably in terms of what is measured, how and why.

The lack of a consistent performance measurement framework together with variable data on project performance results in an inability to benchmark project performance across the construction industry, identify common targets or assess performance improvement. Therefore, this paper seeks to provide a view on how bottom-up data collection and analysis on construction projects should be planned and executed in accordance with a top-down performance measurement framework. A performance measurement framework should address the key performance metrics and the boundaries of digital data required for measurement (top-down) whilst ensuring reliable and accurate data from projects (bottom-up). Through observations of current construction site practices together with a review of academic and industry literature, this paper aims to develop a *data-to-dashboard* strategy that addresses the top-down requirements and the bottom-up digital integration and validation for the purpose of informed decision making in line with top-down performance measurement framework.

2. Performance measurement in construction

Performance measurement in the construction industry can be executed at various levels, from project to organisation, which can then be aggregated to sector or sub-sector level. For example, at a sector level, the *'UK Industry Performance Report'* was developed to evaluate the annual performance of UK construction that included the performance indicators relating to time, cost, profitability, productivity and safety, as well as societal and environmental aspects [6]. At a project level, Jansen van Vuuren and Middleton [4] proposed a performance framework for quantifying project-related metrics across three levels: direct project impacts, broader project impacts and wider societal impacts. However, they found that metrics are subject to individual interpretation which creates difficulties in ensuring consistency and comparability of results between projects and across the industry. Detailed efforts of performance measurement across the sector level and project level are explained in Sections 2.1, 2.2 and 2.3.

2.1. Performance measurement landscape in the UK Construction Industry

A review of construction industry publications was conducted to evaluate how performance measurement is addressed in the industry. Whilst performance measurement is acknowledged as important in most of the influential policy documents (e.g., '*Construction 2025: Industrial Strategy*', '*The Construction Playbook*', and '*Transforming Infrastructure Performance: Roadmap to 2030*'), longitudinal studies of performance measurement are scant. Furthermore, there is not a clear performance measurement framework that guides private and public organisations to measure metrics that drive decisions. The review revealed a top-down approach to performance measurement and a current focus on infrastructure projects and long-term outcomes [5]. Moreover, several performance methodologies and frameworks are still at the high level of definition, with very few tools and actual assessments. Moreover, the review also revealed common top-level performance measurement areas of interest such as organisational capability, digital maturity, project delivery, asset performance, user satisfaction, infrastructure performance, and value. However, these remain in a myriad of intentions to measure, with little evidence of action, let alone benchmarking and decision-making. The actual assessments found can be summarised in Table 1.

Table 1. Performance measurement assessments found in the grey literature.

Assessment	Organisation(s)	Measurement areas	A sample of metrics	Age
UK Industry Performance Report	Constructing Excellence, CITB, Glenigan, BEIS	Project delivery	Client satisfaction, cost and time predictability, productivity, safety, environmental indicators	From 2003 until present
Digital benchmarking report	Digital Transformation Task Group (DTTG) and Mott McDonald	Asset management, digital maturity and commercial	Digital transformation, asset management, asset delivery, asset performance	From 2019 until present
Methodology for quantifying the benefits of off-site construction	University of Cambridge, CIRIA	Project delivery	Cost, time, cost of rework, safety, labour productivity, waste, embodied carbon, energy and water use, noise, air quality	One-off research project (2020)
Impacts of Modern Methods of Construction on the delivery of homes	Homes England	Project delivery and long-term value	Time, cost, labour productivity, pre-manufactured value, safety, waste, energy efficiency performance, maintenance costs, local disruption, wellbeing	One-off research project (2020)
Benchmarking reports	Association for Consultancy and Engineering (ACE)	Organisational	Revenue, costs, profits, financial metrics, productivity, skills. From 2021: Net Zero, Equality, Diversity and Inclusion (EDI)	From the 2010s onwards
Performance measures	National Infrastructure Commission	Infrastructure performance	Volume of consumption, Everyday resilience, Quality of user experience, Environment, Cost	Yearly
Construction statistics in Great Britain	Health and Safety Executive	Project delivery	Work-related ill health (musculoskeletal disorders; stress, depression or anxiety; other), Work-related injuries (fatalities and non-fatalities)	Yearly

2.2. Evaluation of carbon measurement in construction

Environmental assessment metrics are a key component of a robust performance measurement framework. It is imperative that this includes the evaluation of carbon to support the UK's commitment to achieve net-zero greenhouse gas (GHG) emissions by 2050. Carbon metrics provide a standard measurement of GHG emissions that can be used for assessment and comparison of performance against benchmarks; they are essential for evaluating progress towards project-specific carbon reduction targets and national net-zero targets [7]. Determining suitable carbon metrics depends on the level of assessment of the performance framework, for example, a construction project might report on 'upfront embodied carbon' (all emissions associated with materials and construction process [8]), whilst an organisation might report its scope 1, 2, and some of scope 3 emissions in line with GHG reporting protocol. Consistent measurement and reporting of carbon emissions enables performance assessment and benchmarking and is supported through industry initiatives such as UKGBC's Whole Life Carbon Roadmap [9]. However, this relies on robust and reliable data from both construction project impacts and industry databases [10].

2.3. Performance measurement and automated progress monitoring

Onsite construction progress monitoring constitutes a primary part of construction performance measurement where the onsite outputs and inputs are monitored and measured during manufacture and assembly. Some studies have explored the use of automated progress monitoring methods to reduce data collection duration time and increase the accuracy of 3D modelling. For example, Puri and Turkan [11] and Braun et al. [12] proposed a geometry- and appearance-based reasoning approach that supports progress monitoring by detecting and verifying element categories against 3D models. Their approach has improved the detected rates of the as-built elements to a range between 80% to 90%. Similarly, Esfahani et al. [13] investigated a Scan-to-BIM progress monitoring method by modelling 3D elements from as-built point clouds and assessed the impact of automation levels on the accuracy of the generated 3D models. This resulted in a 9%-20% increased dimensional accuracy when compared to traditional manual methods. However, data collection has many practical challenges. For example, real-world data collected from construction sites has many occlusions such as stored materials or temporary works that make it nearly impossible to have 100% accuracy in object detection. Moreover, the automated progress monitoring methods have not been yet utilised to inform better and more reliable decisions in project planning and control. Therefore, existing digital technologies may not be fit-for-purpose yet for automated performance measurement.

2.4. Research gap

To sum up, despite the academic advancements and industry efforts in performance measurement, there seems to be a gap between performance measurement and decision-making. In addition, digital technologies adopted on construction projects generate vast quantities of data that may not be well utilised by management teams, whilst existing automated data collection technologies suffer from practical limitations. Therefore, the measurement process is not consistent, data is not sufficiently interpreted, and results are not fed back up to ensure timely insights for decision-making. As such, the bridge between technology deployment and a consistent performance measurement system underpinned by a quality process has not been sufficiently investigated. This study aims to overcome such a gap by proposing a *data-to-dashboard* strategy for performance measurement, as illustrated in Sections 3, 4 and 5.

3. Research Method

The objective of the study was to provide a view on how bottom-up data collection and analysis on construction projects should be planned and executed in accordance with a top-down performance measurement framework. To support this, observations of a live construction project using several digital technologies for design, construction, and progress monitoring was deemed suitable to understand the main challenges for performance measurement and to develop the *data-to-dashboard* strategy. A mixture of induction and deduction was used to propose the strategy. Inductive reasoning helped the group of researchers to evaluate what is happening in the field, and to define a strategy that would help overcome several limitations into effective performance measurement. Deductive reasoning helped deploy aspects of the strategy for productivity and carbon measurement. The case study selected was a live construction project of a commercial development located in London, UK. The project combines some elements of traditional construction (such as in-situ concrete floor slabs) with innovative modern methods of construction and has a specific focus on improving productivity, as well as ambitious carbon targets. Project data consisted of several workshops, one-to-one discussions with project stakeholders, access to BIM models, programmes, cost data, and access to the digital data collected by the project delivery team.

4. Performance measurement and digital integration

To develop the 'data-to-dashboard' strategy, a theoretical framework of performance measurement and digital integration is proposed as shown in Figure 1. This is based on the total quality management principles, specifically on the PDCA (Plan-Do-Check-Act) quality cycle [14]. The three underpinning components of the framework are 1) performance metrics which are a defined set of indicators such as environmental, social and productivity indicators, 2) digital data capture tools and integration processes which are required to help trades and managers collect and connect the multi-source project data related to the performance metrics, 3) data analysis tools to provide insights into the measurements of metrics together with their reliable predictions to indicate the future states. Figure 1 shows that the dynamics between the three components exhibits three major benefits of performance measurement under total quality management principles: A – ensuring representative, timely and accurate measurement of metrics by using digital tools to replace manual documentation which also guarantees the efficient data exchange and feedback process; B – ensuring consistent measurement of metrics and the prediction of future states by using standard data analysis methods and predictive analytics; and C – ensuring required data cleaning to ensure data input quality and streamlined data analysis workflow. These benefits enable the transformation of data into meaningful insights and allow the ultimate goal to be achieved, which is to inform better decisions to help project stakeholders plan, adjust, correct site activities and improve performance. The three components are organised in a structured workflow, which is the data-to-dashboard workflow described in Section 5.

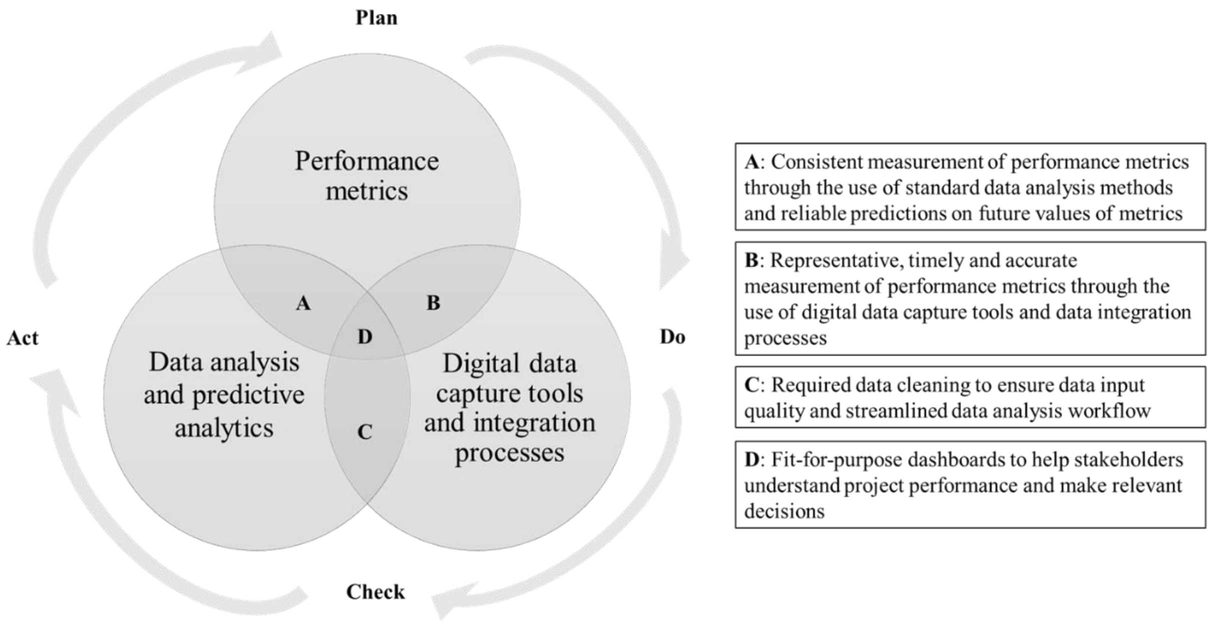

Figure 1. Performance measurement and digital integration.

5. Data-to-dashboard strategy

Based on Figure 1 and the observations in the case study, a data-to-dashboard strategy is developed to encapsulate the three process components (i.e., performance metrics, digital data capture and integration, and data analysis) for improved stakeholder decision-making processes, as shown in Figure 2. The strategy starts with the engagement of key stakeholders and supply chain partners (i.e., client, designers, contractors, subcontractors) as the first step of the PDCA quality cycle. In the case study, client leadership was found to be a paramount enabler to deploy the strategy. The client's willingness to involve key players and demonstrate the project's outcomes helped set up the data-to-dashboard strategy. This included project managers, digital managers, lead designers, relevant subcontractors, planners, and commercial managers. The subcontractors are essential information providers for task-level productivity measurements.

Once the key stakeholders and supply chain partners are gathered, a definition workshop should be held to help the project management team decide the key metrics that are needed to drive decisions in the project. Key metrics could consist of leading indicators (to inform the process and future trend) and lagging metrics (to inform current status and results). Metrics should be defined in line with the shared goal of the key stakeholders and supply chain partners and the project team's vision of the project performance and outcomes. This aligns motivation and incentives for consistent performance measurement across the different stakeholders.

During the workshop, the project stakeholders should discuss the frequency of data collection and analysis to inform the management of specific work packages. The specification of the granularity of data is also required as it informs data collection and analysis within specific timeframes. For example, detailed task-level data would be required for evaluating and influencing specific trade work, whilst overall productivity would require aggregated work package level information. The calculation of the defined metrics needs to be consistent with the granularity of the collected data. The data and metrics identified at this stage should also allow the project team to evaluate project performance against industry benchmarks in terms of quality, time, environmental or social impact. This highlights the importance of planning data collection and metrics that allow the project performance to be evaluated at multiple levels, from specific tasks to work packages to the overall project.

When the key metrics and data needs are defined, the key stakeholders and supply chain partners move on to identify the data points needed to measure the key metrics, entering the second step of PDCA to implement measurements. This primarily relates to identifying suitable technologies to capture the data needed and to integrate data from multiple sources, to ensure quality in the data. For example, the concrete curing team may install concrete sensors to automate data collection of curing temperature and concrete strength, meanwhile, the sustainability team may implement systems to collect information about material deliveries and waste generated on site. After the technological and digital tools are determined and arranged, each responsible team has to mobilise these technologies and processes to streamline data capture. Data integration is required when specific decisions rely on data collated from different data sources and exchanged through common data protocols. It is essential at this technology deployment stage that there is a clear understanding of the functionality of a specific technology to avoid repeated, unnecessary or even inconsistent data collection. The data collected should link to the metrics identified and provide useful insights for decision-making or evaluating project performance. The case study has shown the need to triangulate data sources for a single event. On the one hand, this was necessary due to the inability of some systems to capture the data at the right granularity and the needed reliability. On the other hand, however, measuring the same event several times might be deemed as wasteful. Furthermore, data quality was an issue that had to be reviewed manually. Therefore, there are still important practical limitations for the deployment of an automated data collection process.

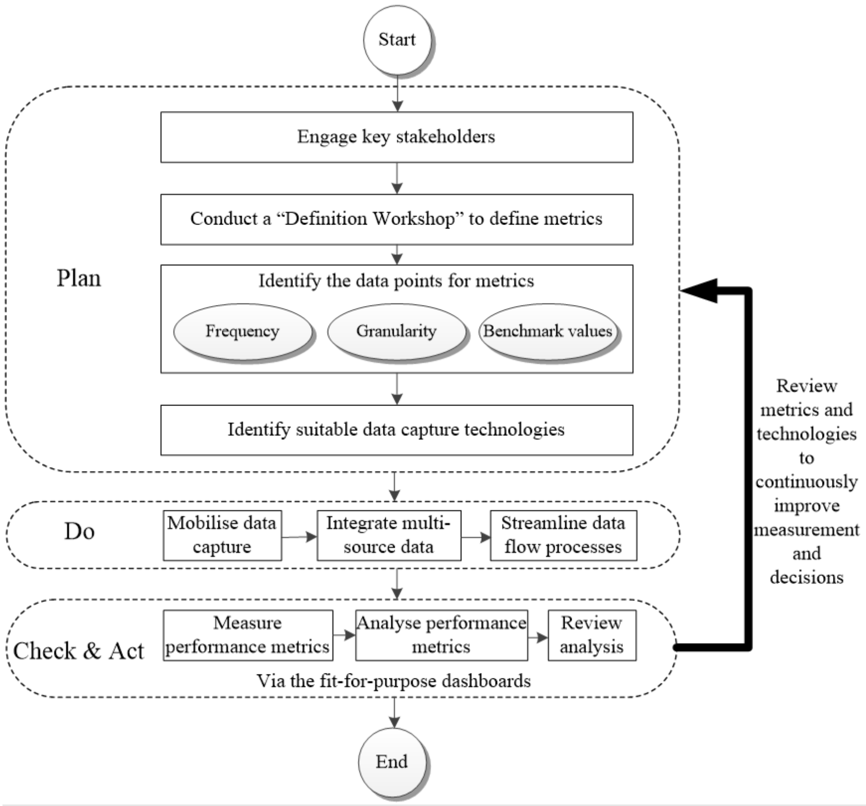

Figure 2. The data-to-dashboard strategy.

Corresponding to the last two steps of the PDCA cycle, the key stakeholders and supply chain partners work together to measure, analyse, review, and improve performance metrics. This could be done via the dashboard such as a web interface showing the value of metrics and insights. Historical data are useful for trades and management teams to learn from previous hurdles and continuously improve the work in the upcoming schedules. For example, the historical non-conformance records may indicate the potential areas of pipe quality defects and inform trades about the preventive measures for pipe installation. Based on the measurement results, the previously defined key metrics are subject to iterations of changes and adaptation considering the dynamic progress of projects. The performance measurement cycle iterates until the project is completed.

6. Discussion

6.1. From project to work package level, and from work package level to activity level

Performance measurement should be conducted following a hierarchy of key performance metrics. The scope and aggregation level of metrics vary according to different perspectives and requirements of stakeholders. For example, at the project level, the client may be interested in the schedule and the cost variance of the whole project quarterly. At a work package level, however, installation teams such as mechanical trade managers may be more concerned about the installation speed of the overall ducts and piping system. From the work package level to a more detailed activity level, trades play a dominant role in measuring productivity. This detailed level of measurement requires a higher granularity of data from appropriate data capture tools. The varying requirements of metrics for different stakeholders also influences the time frames for data collection and analysis. Therefore, the performance measurement not only requires consistency in metrics definition but also requires a hierarchy of measurements respecting project, work package and activity levels. This must be defined early in the definition workshop.

6.2. Productivity measurement

Productivity, which is the output per input, is a measure of the efficiency of utilisation of resources. The inputs or resources in construction include labour, material and equipment. During the definition workshop, the project stakeholders should decide which of these inputs need to be considered in the analysis at each level of analysis. Considering more inputs ensures that more insight is provided by productivity as a leading metric. Therefore, at higher levels such as the project or work package, it might be useful to calculate output per multiple inputs, i.e. multifactor productivity. However, at lower levels such as the activity or task, it might be more practical to calculate output per labour hour, i.e. labour productivity (m^2/mh) or simply output per time, i.e. production rate or speed (m^2/day).

According to the PDCA process, the management team must review the productivity data at selected intervals. For instance, the leading productivity metrics for the structural frame can be calculated on a level-by-level basis, whereas the façade installation can be assessed every week. Figure 3 depicts the labour productivity for the structural frame measured in m^2 of floor plate per labour hours used. Level 6 showed the highest productivity whereas level 9 showed the lowest productivity. Comparisons can be made *within* and *between* projects to benchmark current performance and to identify the root cause for low and high performance. The observations have shown that higher variability levels of daily installation are associated with lower production rates and lower labour productivity. However, the measurement of low productivity is not only a signal of using more resources than needed but also a warning sign of the need for enhanced collaborative planning and improved logistics at the operational level between trade contractors. With this level of insight, the management team can make decisions that can ultimately reduce process waste and add value.

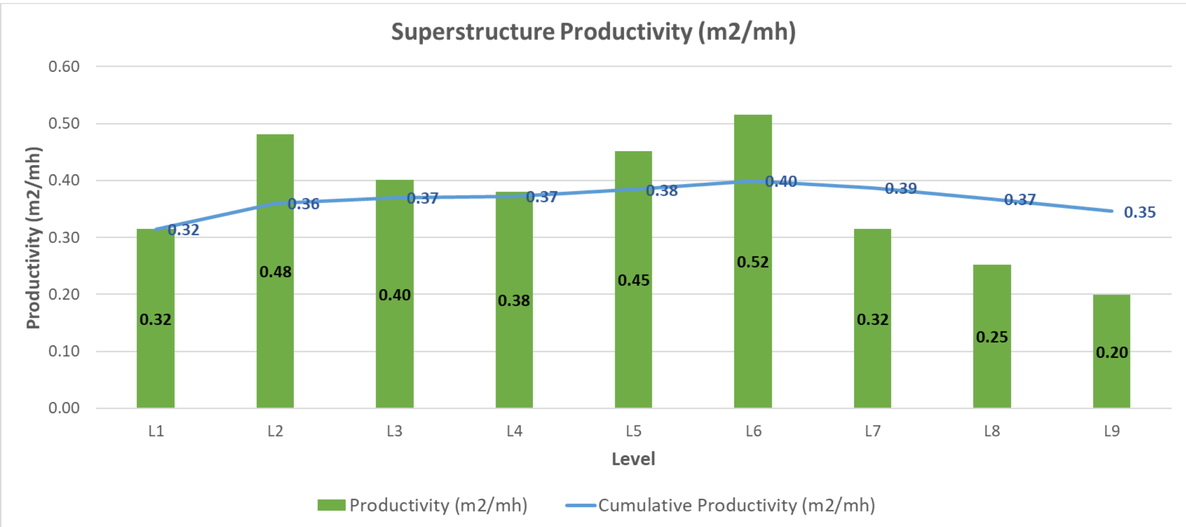

Figure 3. Leading productivity metric for the superstructure structural frame (using dummy data).

6.3. Carbon measurement

The data-to-dashboard strategy emphasises the importance of understanding the purposes behind collecting data on a construction project and identifying the insights that are expected from the analysis and interpretation of that data. Applying this to the assessment of carbon metrics on construction projects, during the construction phase, project data about materials and site processes is needed to accurately calculate the upfront embodied carbon. Construction projects should assess how the digital tools and processes in place can be used to collect data required for the embodied carbon assessment. This includes accurate data on material quantities and specifications (e.g. grade of concrete supplied and cement replacements used, manufacturer-specific embodied carbon factors for material supplied, etc.), waste generated (amount, type, disposal method), delivery information (vehicle type, distance travelled), and other construction process-related carbon impacts such as site energy use and fuel use.

Following the PDCA process, the data collected should be analysed and compared to the embodied carbon model generated during the design phase to ensure that assumptions regarding key aspects are valid and that the project is on track to meet any carbon targets it may have. This should be conducted as the project progresses as the feedback loop allows for assessment of progress and implementation of remedial actions or interventions if necessary to ensure the project meets performance targets.

6.4. Technology limitations

Nowadays, digital technologies and sensors are being increasingly used in modern construction sites [12,13]. However, these technologies offer the opportunity to acquire vast quantities of data that might not be processed to obtain meaningful insights. This *'data overload'* is argued to hinder the potential top-down measurement value offered by the adoption of digital technologies. Automating data collection using multiple types of technology may also create data uncertainty and challenges. Therefore, a full assessment of the functionalities of planned technologies should be made before stakeholders deploy them to capture data. Technology deployment should be in line with the specific needs of project stakeholders, which should be identified during the definition workshop.

Human intervention is required for data cleansing and post-hoc verification to ensure the reliability and validity of the collected data. Seamless data integration remains challenging due to a lack of standard data protocols and a manual approach being required in digital workflows to integrate multi-source data and create visual representations in dashboards. This is evident from general industry experience and was also observed on the live construction project. The case study also showed that digital managers deal with *blind spots* in the data as the existing technologies do not necessarily collect data at the appropriate level of granularity, or systems are unable to extract data in an intended way. For example, installation data might have the start and end time but lack the labour used for the installation. Not having labour data at the right granularity level is a blind spot in the measurement system as it results in being unable to accurately calculate labour productivity.

Dashboards are commonly used in industry for presenting the data related to performance of construction projects. However, dashboards also present another form of *'data overload'* as they depict several data points and graphs without necessarily providing a clear direction and can be difficult to interpret. Dashboards should therefore be designed to present the most relevant metrics needed by project stakeholders over time.

7. Conclusions and further research

Despite the many measurement frameworks and actual assessments found in the grey literature, the relationship between performance measurement and decision-making remains unclear. Our review shows that most performance frameworks encompass long lists of lagging metrics with little clarity on benchmarks and continuous improvement. The lack of a consistent performance measurement framework together with variable data on project performance results in an inability to benchmark project performance across the construction industry, identify common targets or assess performance improvement. The extensive use of digital technologies would support automated data collection to inform timely decisions. However, the plethora of digital technologies adopted on construction projects by organisations generate vast quantities of data that seemingly conflict with organisations' abilities to evaluate and transform it into meaningful insights. Based on the PDCA approach, this paper presented a data-to-dashboard strategy that demonstrates how bottom-up digital integration and validation should align with top-down performance measurement and decision-making requirements. The strategy encapsulates three process components: definition of value-adding performance metrics, digital data capture tools and integration processes, and data analysis for improved stakeholder decision-making processes. Observations from a live construction project were used to support and test the development of the strategy; this highlighted the importance of key stakeholders and supply chain partners working together in a PDCA quality cycle to ensure that the digital technologies and data analysis is providing the necessary insights to review and improve project performance. The proposed strategy ensures a consistent definition of metrics early in the project, and the continuous measurement of leading indicators to assess project performance. However, the multi-source data integration and the translation of information into knowledge remain challenging issues and therefore cause difficulties for stakeholders to implement timely corrective measures in projects. Current limitations of the strategy include the lack of an agreed performance framework for activities, work packages and projects. To expand the scope of the data-to-dashboard strategy, an industry-wide and multi-level performance measurement framework will be investigated in future research work.

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