Mapping Digital Solutions for Productivity and Disruption Monitoring in Construction

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Abstract -

Productivity and disruption monitoring remains a persistent challenge in construction projects. Although digital technologies such as Internet of Things (IoT) sensors, Building Information Modeling (BIM), computer vision, and AI-driven analytics have been introduced, practitioners often lack systematic guidance on aligning these tools with specific monitoring objectives to improve productivity and reduce waste and delays. This study first identifies key productivity measures and disruption indicators. Current digital approaches for capturing these are then clustered into six classes: sensor-based, vision-based, location-based, apps, digitised legacy documents, and audio-based systems. A review of the existing literature is conducted to map the metrics and indicators with suitable digital solutions and assess their maturity. A preliminary case study demonstrates the applicability of the proposed digital solutions in response to monitoring needs. Future work includes developing a decision-support system to select appropriate technologies tailored to monitoring requirements.

Keywords -

Digital solution; Productivity; Disruption; Monitoring

1 Introduction

The construction industry suffers from low productivity growth and persistent schedule and cost overruns that degrade project performance worldwide. Numerous studies have identified that supply chain issues, rework, and disruptions are dominant contributors to poor outcomes [1]. A recent systematic review of construction productivity found that it is shaped by interactions among organisational, technical, and managerial factors, making productivity improvement a persistent industry challenge [2].

Accurate productivity measurement is essential for identifying performance gaps and guiding improvements. Without measurement, inefficiencies remain hidden, causing resource waste, delays, and higher costs [3]. Monitoring productivity enables informed decision-making, helping managers allocate labour and equipment effectively and assess the impact of interventions [2, 4].

Disruption events directly affect construction flow and project performance [5]. Unlike delays, which are typically identified after schedule deviations occur, disruption manifests during execution as interruptions to workflow continuity, resource utilization, and productivity [4]. As such, disruption functions as an early-warning signal; systematic monitoring enables project teams to detect performance degradation before inefficiencies accumulate into delays or cost overruns [6]. However, organisations frequently struggle to establish the structural mechanisms needed to systematically capture, interpret, and act on disruption data, allowing disturbances to propagate into cascading delays [5].

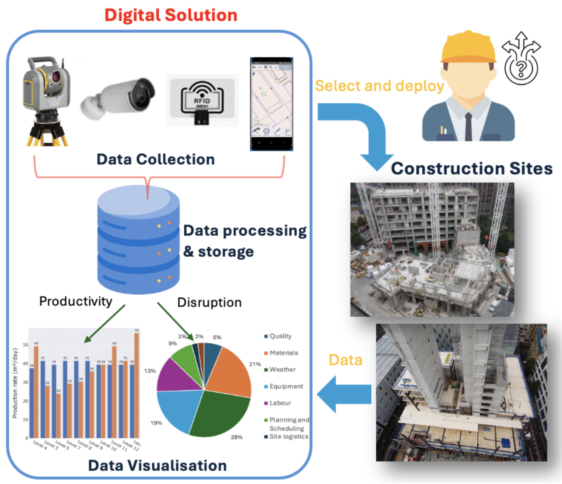

Figure 1. Illustrating the research gap: stakeholders need a tool to support decision-making in selecting appropriate digital solutions for productivity and disruption monitoring across different construction sites.

Monitoring productivity and disruption plays a key role in enabling automation in construction. Real-time measurement provides the basis for identifying opportunities for automation and robotic applications to improve productivity and mitigate disruptions. Building on these data-driven insights, digital solutions can support automated execution and adaptive construction processes. Linking measurement, decision-making, and automation can significantly enhance project performance.

However, digital monitoring of productivity and disruption faces challenges. Construction firms vary widely in digital maturity, making it difficult to align solutions with capabilities and goals [7]. Unstructured monitoring requirements complicate translation into actionable designs [8]. With the proliferation of ConTech solutions, adoption is often siloed and ad-hoc, lacking systematic evaluation and integration, which limits their ability to generate actionable insights [9]. Therefore, this study addresses the question: How can organisations systematically integrate monitoring requirements with digital solutions to generate data-driven insights for productivity improvement? It proposes a structured approach to help construction companies efficiently select suitable digital solutions, as shown in Fig. 1.

2 Literature Review

2.1 Construction Productivity

Construction productivity refers to the efficiency with which inputs (labour, materials, equipment) are transformed into outputs, commonly expressed as output-to-input ratio and measured as work quantity per unit of labour, time, or cost [10]. Beyond this quantitative ratio, productivity is increasingly understood as dynamic and context-dependent, influenced by work conditions, management practices, and disruptions. Empirical studies have shown that productivity fluctuates in response to changes, interruptions, and cumulative disruption impacts [11]. Contemporary research defines construction productivity as the ability to achieve planned output efficiently whilst minimising productivity losses from disruptions and waste [2, 12]. This definition emphasises real-time measurement of outputs and inputs to accurately reflect execution efficiency under site conditions and inform production planning and control. However, existing research largely focuses on vision-based approaches (i.e., outputs)[13], with limited attention to how other digital technologies can be selected and aligned to simultaneously measure inputs.

2.2 Construction Disruption

Disruption is conceptualised as an unplanned event or condition that adversely affects work execution, resulting in reduced productivity, increased costs, and potential schedule impacts [6]. Disruption is conceptually distinct from delay and waste. Delay refers to time overrun relative to the planned schedule [1]. Whilst disruptions can cause delays, productivity losses may occur without immediately affecting critical path activities. Waste refers to non-value-adding activities consuming resources without contributing to progress [6]. Both delay and waste are often consequences rather than disruptions themselves [2]. As such, a timely detection of disruptions can explain productivity variability and provide site managers with additional insights into performance. Crucially, this is relevant to multi-tiered construction, where agents in the upper tiers (i.e., general contractors) have less visibility into data and outputs from lower tiers (i.e., trade contractors). Disruption is thus a multidimensional performance anomaly manifested through adverse impacts on schedule, productivity, and quality. By identifying and addressing disruptions early, teams can proactively prevent downstream effects. However, disruption monitoring has been less widely addressed than productivity monitoring, partly due to a lack of systematic definitions of disruption causes and associated digital measurement solutions.

2.3 Digital Solutions for Construction Monitoring

Traditional manual monitoring is fragmented and reactive, hindering rapid detection of productivity changes and disruptions. Digital solutions provide real-time, objective, and automated observation via sensors, cameras, and mobile applications. Vision-based approaches using laser scanning and computer vision automate progress monitoring by comparing as-built conditions with planned or BIM-based models [14]. Advances in object recognition and multi-object tracking enable detailed activity-level assessments [13, 15], providing a basis for the project status information digital twin construction [16]. Real-time locating systems (RTLS) using UWB and BLE monitor movement and interaction of workers, equipment, and materials, enabling quantitative analysis of workflow, space utilisation, and non-productive time [17]. Such approaches provide critical inputs for understanding disruption mechanisms related to congestion, waiting, and out-of-sequence work. In addition, mobile devices facilitate on-site data collection and decision support [18]. IoT frameworks enable the integration of heterogeneous data sources for real-time project performance analysis [19]. Audio-based monitoring has emerged as a viable alternative when visual sensing is constrained. Research has investigated the use of ambient sounds and machine learning to identify activities, equipment operation, and safety-critical events [20]. Despite the wide range of options for capturing real-time data, selecting suitable digital solutions tailored to specific requirements remains challenging for stakeholders lacking sufficient technology knowledge.

As the industry moves toward real-time monitoring of productivity and disruptions, the lack of unified disruption indicators creates uncertainty in selecting appropriate digital solutions [8, 13]. In this study, disruption indicators are defined as quantifiable measures captured and analysed in real-time to support data-driven decision-making, and digital solutions as purpose-built systems integrating one or more technologies for tasks such as data collection, processing, storage, and performance visualisation. Despite extensive research on individual technologies, no framework systematically links productivity measures and disruption indicators to multiple digital solutions; this study addresses that gap.

3 Methodology

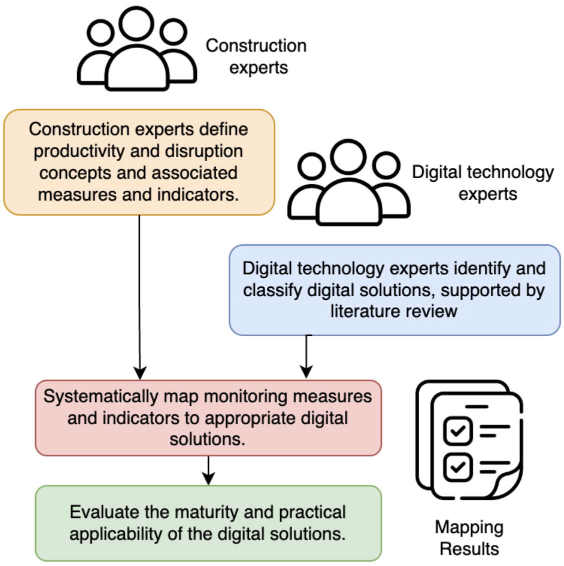

Figure 2. Overview of the proposed methodology.

The overall methodology comprises four key steps, integrating inputs from construction experts and digital technology experts, as illustrated in Fig. 2.

1. *Definition and identification of productivity measures and disruption indicators:* This step involves construction experts defining productivity and disruption concepts, along with associated measures and indicators, supported by evidence from multiple case studies in UK-based projects [4]. To explain variability in production and productivity, it was necessary to standardise data collection on blockers to productivity, which are here defined as disruptions. An initial list of disruptions was derived from Rathnayake and Middleton [2], piloted across three projects, and refined through multiple cycles of industry engagement. Three construction engineering experts were involved in this process.

2. *Identification and classification of digital solutions for data collection:* This step involves digital technology experts identifying and classifying available digital solutions for construction monitoring, supported by a literature review of major construction journals. The literature search was conducted using databases including Scopus, Web of Science, and Google Scholar, with keywords such as "construction monitoring", "productivity monitoring", "disruption", "digital construction", and "computer vision". Approximately 100 key papers were identified through database searches and subsequently selected based on relevance through expert screening (see Section 2.3). These technologies include those capable of capturing visual, spatial, acoustic, and other physical data. Based on the type of data collected and their applicability to monitoring productivity and disruptions, the solutions were grouped into categories to maintain a manageable level of abstraction. This classification enables users to first identify suitable solution types and then refine application details.

3. *Mapping productivity measures and disruption indicators to digital solutions:* This step systematically maps productivity measures and disruption indicators to the most appropriate digital solution types for monitoring. The mapping was conducted through close collaboration between construction professionals and digital technology experts, ensuring alignment between monitoring objectives and technological capabilities. The resulting mapping provides a structured framework for evaluating the suitability of digital solutions for specific monitoring goals.

4. *Evaluation of maturity and practical applicability of digital solutions:* The final step evaluates the maturity and practical applicability of the identified digital solutions. This includes assessing technological readiness, accuracy, scalability, cost, and operational feasibility. Understanding the strengths and limitations of each solution type provides a foundation for selecting appropriate monitoring strategies and supports the effective deployment of digital solutions in practice.

Overall, this study integrates knowledge from construction and digital technology experts to bridge the gap between the requirements for real-time monitoring of productivity and disruptions and the widespread availability of digital solutions that are often underutilised or ineffectively selected in construction projects. It provides a foundation for developing a structured approach that links monitoring requirements to the development and deployment of digital solutions in construction.

Table 1. Types of digital solutions for productivity and disruption monitoring.

Solution Type	Description	Examples
Sensor-based Monitoring Systems	Use of IoT-enabled sensors to collect real-time data related to equipment condition, environmental parameters, and worker activities.	Equipment condition monitoring; process monitoring; energy usage monitoring
Vision-based Monitoring Systems	Use of cameras or laser scanners to observe site activities, detect events, and track construction progress.	Progress monitoring; working conditions monitoring; automated quality inspection
Location-based Tracking Systems	Technologies such as GPS, RFID, or BLE used for real-time tracking of workers, equipment, and materials on construction sites.	Inventory tracking and status updates; tool and equipment tracking and assignment
Web-based / Mobile Applications	Web- or mobile-accessible user interfaces for data entry, storage, analysis, and visualisation.	Visualisation of financial KPIs; sales tracking; progress payment tracking; integrated change management and issue reporting between design and construction
Digitised Legacy Documents	Conversion of legacy documents (e.g., handwritten notes, PDFs, word documents, spreadsheets) into structured digital formats.	Digitalisation of printed labour task allocation sheets into structured digital records
Audio-based Monitoring Systems	Use of microphones and acoustic analysis techniques to capture and interpret sound patterns from machines, environments, or workflows for monitoring and anomaly detection.	Detection of abnormal machine noises; noise-level compliance monitoring; identification of process issues through sound patterns; recording managerial instructions or voice logs

4 Results

4.1 Productivity Measures

Three productivity metrics were defined: production rates (output/duration) and labour productivity (output/worker-hour), and cost-effectiveness (output/cost) for both planned and actual values. The output is measured as progress, which refers to the amount of work completed over time, such as the number of square meters constructed each day [21, 15]. Inputs are measured using labour data, which can be monitored by recording labour hours or workforce utilisation on each activity or work package [22]. Cost can be tracked by estimating expenditures and resource consumption over time [10, 6].

Two additional measures are derived from the programme and BIM models. The programme provides the planned duration for activities and work packages per location, while BIM models provide the planned quantities over time, and serves as a baseline for monitoring progress and productivity [23]. Together, these measures enable real-time monitoring of productivity metrics and allow comparison with planned values.

4.2 Disruption Indicators

Compared to productivity, construction disruption lacks consistent measurement metrics. Unlike traditional disruption measures used in claims analysis or post-event evaluation [24], our indicators are designed to support continuous monitoring through digital solutions, enabling early detection of emerging disruptions.

The resulting indicator set is organized into ten major categories: labour, materials, equipment, planning, logistics, health and safety, design and constructability, quality, weather, and external factors. These indicators span multiple dimensions of project performance. Labour-related indicators capture workforce availability and efficiency losses [22], while material and equipment indicators reflect interruptions in resource flow [10]. Planning and logistics indicators represent workflow reliability and spatial constraints [21], and design and quality indicators capture upstream information gaps and rework-related disturbances [6]. Weather and external indicators account for exogenous shocks affecting site operations [1]. This multidimensional structure supports a system-level understanding of disruption as a dynamic production anomaly rather than a single, isolated event.

We further divided them into 33 monitoring indicators, as shown in Section 4.5. These indicators specify information that enables digital solutions to directly detect and monitor events during execution, as detailed in the subsequent mapping sections.

4.3 Classification of Digital Solutions

In Section 2.3, we reviewed digital solutions for construction monitoring and further classified these techniques into six solution categories, as shown in Table 1. These solution types include sensor-based monitoring systems, vision-based systems, location-based tracking systems, web-based and mobile applications, digitised legacy documents [25], and audio-based monitoring systems. A

Table 2. Mapping of productivity measures to digital solution types (H = High maturity, M = Medium maturity, L = Low maturity).

Productivity Measure	Sensor	Vision	Location	Apps	Digitised Documents	Audio
Progress	M	H		H	M	L
Labour	H	M	M	H	M	L
Cost				H		
Planned duration (from programme)				H		
Planned quantity (from BIM model)				H		

detailed description of each solution type is provided in Table 1. This classification also builds on the work of Yilmaz et al. [26], who identified 58 digital solution areas for construction SMEs through eight interactive workshops with 70 UK SMEs. By organising these solutions into the six categories presented here, we cover most of the 58 solution areas identified by Yilmaz et al. [26], some of which are provided as examples in Table 1.

To further evaluate the applicability of these digital solutions, we define three maturity levels as follows: High maturity technologies are well-established, commercially available, and easily integrated into existing workflows. Medium maturity technologies are technically feasible and validated in pilot studies but require configuration, integration, or specialist expertise and are not yet widely adopted. Low maturity technologies are experimental, primarily at the prototype or conceptual stage, and require further development and validation before reliable application in construction projects.

4.4 Mapping of Digital Solution to Productivity Monitoring

Table 2 presents the mapping of construction productivity measures to different categories of digital solutions, along with their corresponding maturity level. Progress data are most effectively captured using vision-based and application-based solutions (H), whereas audio-based monitoring remains at a low maturity level (L). However, voice logging is an emerging area of development. Labour data can be monitored efficiently with sensor- and application-based systems (H), while location- and vision-based systems provide medium-level support. Cost, programme, and BIM model data are primarily supported by high-maturity, application-based solutions, reflecting the widespread use of integrated project management software in industry practice.

4.5 Mapping of Digital Solution to Disruption Monitoring

Table 3 presents a detailed mapping of 33 disruption indicators to appropriate digital solution types, classified by maturity levels. Compared to productivity measures, disruption indicators capture deviations in workflow execution, requiring targeted monitoring approaches for early detection.

Software applications represent high-maturity solutions widely used in construction, from which most disruption indicators can be derived. However, their reliance on manual input may delay early warnings, and AI-driven analysis is needed to extract critical information from large datasets. Sensor-based systems are mature for monitoring equipment, materials, and weather-related disruptions, while wearable sensors such as IMUs are emerging for labour activity monitoring. Tracking technologies are well established for logistics disruptions and show further potential in material, equipment, and safety tracking (e.g., detecting workers in hazardous zones). Vision-based systems are widely applied to site monitoring but depend heavily on advanced AI and are sensitive to occlusion and lighting conditions; their role in disruption monitoring is expected to grow as reliability improves. Application-based solutions provide broad coverage but are limited by data latency from manual input, while digitisation and AI-based document analysis can unlock valuable information from legacy data. Audio-based monitoring is less common and primarily used for equipment anomaly detection; however, advances in voice logging may allow abnormal work patterns to be recorded efficiently.

5 Preliminary Study

A preliminary study was conducted with a construction company on a recent project. Productivity had previously been recorded manually and calculated monthly or over longer periods using spreadsheets. Although the company sought more real-time monitoring, it lacked awareness of suitable digital solutions, making technology selection difficult. Using the mapping table developed in this study, the company's monitoring needs were systematically linked to relevant digital solution types, enabling a more structured and objective selection process.

After further criteria-based discussions, several solutions were selected and implemented. Two CCTV systems were deployed to capture image data, and progress information was extracted using an advanced segmentation approach (SAM2 [27]). This selection was guided by the mapping framework, which identified vision-based so-

Table 3. Mapping of disruption indicators to digital solution types (H = High maturity, M = Medium maturity, L = Low maturity).

Category	ID	Disruption Indicator	Sensor	Vision	Location	Apps	Digitised Docs	Audio
Labour	1	Worker attendance variance			M	H	M	M
	2	Labour idle time	L	L		M		L
	3	Reduced working speed	L	M		M		L
	4	Labour output rate below plan		M		H		L
Materials	5	On-site material availability	H	L	M	H	M	
	6	Material delivery delay	M		M	H	M	
Equipment	7	Equipment availability rate	H	M	M	H	H	M
	8	Equipment downtime	H	M		H		M
	9	Equipment maintenance duration	H	M		H		M
Planning	10	Out-of-sequence work		M	M	M	H	
	11	Trade handover delay		M	H	M	H	
	12	Work area access delay		M	H	M	H	
Logistics	13	Crane utilisation conflict	H	M		H		
	14	Loading/storage area congestion		M	H	M	H	
	15	Material transport time		M	H	M	H	
	16	Material unavailability at work-face		M	H	M		
	17	Worker travel time to welfare			H	M		
Health & Safety	18	Safety induction time				H		
	19	Safety non-compliance events		M	M	H	H	
	20	Safety incidents / near misses		L		H		
	21	Safety stand-down duration		M		H		
Design & Constructability	22	Missing design information				H	M	
	23	Design errors / clarifications				H	M	
	24	Change order frequency				H	M	
	25	Design clash occurrence				H	M	
Quality	26	Quality non-conformance		M		H		
	27	Rework duration		M	M	H		L
	28	In-process corrective work		M		H		L
Weather	29	High wind events	H			H		M
	30	Heavy rainfall events	H			H		M
	31	Extreme temperature exposure	H			H		M
	32	Snow / ice conditions	H	M		H		M
External	33	External operational interruptions				H	H	

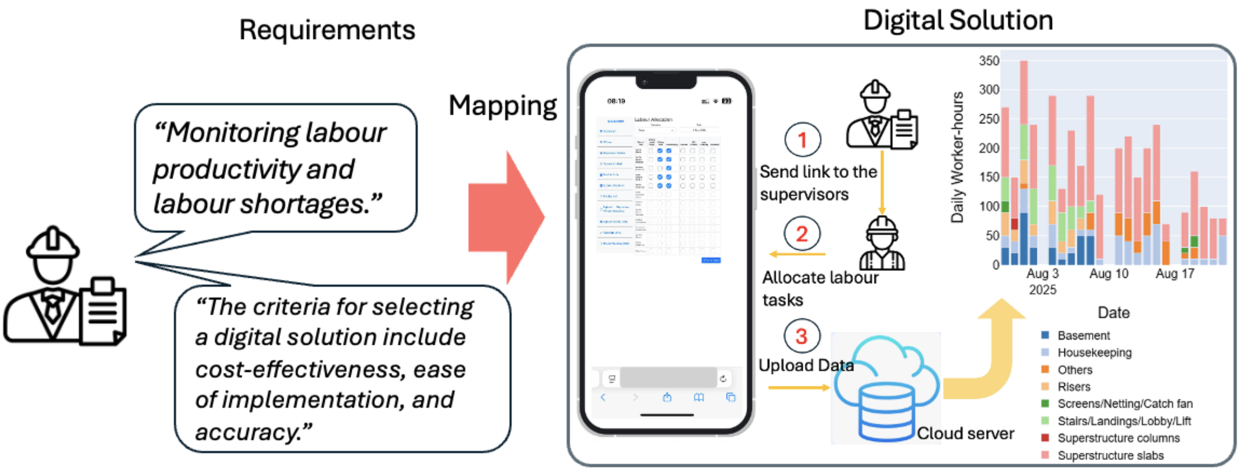

Figure 3. Case study of labour productivity and disruption monitoring.

lutions as suitable for progress monitoring due to their high maturity and ability to capture output-related data. Due to space constraints, detailed methodology and results will be reported in a future publication.

Labour data was initially captured through the turnstile system, which only records site entry and exit and does not capture task-level activity information for labour productivity measurement. A web application was developed and deployed on a cloud server (see Fig. 3). Each working day, site managers assigned activities to construction crews, while supervisors used the system to allocate tasks to workers. The application allowed supervisors to monitor labour input for each activity and to send messages reporting labour shortages for specific activities or task re-allocations to managers. This approach addressed a key disruption indicator, labour shortage, by enabling daily visibility of workforce allocation and deviations from planned activities.

The web application has been in use on-site for over two months. Data collected through the system has been successfully used to monitor daily labour productivity. Alerts can be generated by supervisors to identify potential disruptions caused by labour shortages, enabling site managers to reallocate labour accordingly. During the preliminary study, positive feedback from the company confirmed that the initial requirements of productivity monitoring had been met. Furthermore, the use case demonstrates how the proposed mapping framework supports construction managers in selecting and deploying digital solutions by linking monitoring requirements with appropriate technologies. The daily collected data also enabled timely decision-making, such as reallocating labour tasks.

However, disruption measurement of labour shortage using the web application relies on manual input and does not support fully real-time or automated monitoring. Location-based tracking systems may enable more automated and real-time disruption detection in the future, although their maturity remains limited. The mapping also highlights potential research directions for industry implementation.

6 Discussion and Conclusion

This paper proposes a structured mapping approach of digital solutions for productivity measurement. To achieve this, we first identified the key productivity measures and disruption indicators. The various digital solutions were then clustered into six groups to facilitate straightforward mapping. Based on this framework, two mapping tables were created, and the maturity of the available digital solutions was evaluated. A preliminary study was conducted to gather user requirements, apply the mapping tables, and select and deploy the most suitable solution. This approach provides a practical guideline for construction companies to efficiently deploy digital solutions for monitoring productivity and disruptions.

However, the mapping tables require further refinement through additional pilot studies and by linking to a broader range of off-the-shelf solutions. Further work is also needed to deepen disruption-focused analysis and validate the effectiveness of these solutions through additional case studies. The selection criteria can be enhanced by incorporating additional factors to support improved decision-making.

Finally, the proposed framework can be developed into a decision support tool that leverages the mapping tables and selection criteria to make solution selection more objective and automated. By enabling the systematic selection of sensing and monitoring solutions, the framework supports reliable data collection and digitalisation, providing a foundation for construction automation, including data-driven decision-making and robotic applications.

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