Digital Transformation in Building Construction: Challenges, Opportunities, and Combined Impacts of Digital Solutions

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Abstract

The Architecture, Engineering, and Construction (AEC) sector is undergoing a profound transformation driven by digital innovations to enhance efficiency, sustainability, and business success. However, given the vast and heterogeneous data generated across building lifecycle stages, the sector faces challenges stemming from fragmented processes and limited interoperability. This paper presents a systematic literature review of digital solutions investigated in the AEC sector, focusing on their application and integration over the last decade. The study categorises digital solutions into three main areas—Data Acquisition, Digital Fabrication and Automation, and Digital Information—and identifies six primary digital solutions within these areas. Using bibliometric analysis, Venn diagrams, and a multi-value assessment tool based on the three KPIs, Technology Readiness Level (TRL), Application Areas Level (AAL), and Integrability Level (IL), the research highlights the sector's current fragmentation and the persistent challenge of interoperability. Results show a strong presence of Information Modelling solutions, often integrated with monitoring technologies, but limited cross-category integration. While digital tools offer significant opportunities such as real-time monitoring, enhanced collaboration, and sustainability improvement, technological, organisational, and regulatory barriers hinder their full potential. The paper underscores the need for integrated frameworks and shared standards to address these challenges, suggesting that digital transformation aligned with ESG goals can yield more resilient, efficient, and sustainable construction practices.

Keywords: Surveying Technologies, Monitoring Technologies, Off-site Construction, Building Information Modelling, Extended Reality

1. Introduction

The Architecture, Engineering, and Construction (AEC) sector is undergoing a digital transformation driven by innovations and digital solutions, defined as procedures, methodologies, and tools based on digital technologies

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designed to address common needs and enhance efficiency, competitiveness, resource utilisation, and sustainability.

Companies primarily view this process as an aid to developing new products, representing an evolution that yields benefits, e.g., increased labour productivity and reduced costs and waste [1]. The success of digitalisation within an organisation often depends on effective employee engagement, clear communication of its benefits, and the encouragement of experimentation with new solutions. Therefore, beyond the technical aspect, digital transformation must directly involve all stakeholders of the sector, bringing changes to the business model and procedures.

Digital tools support the entire building lifecycle, encompassing design-related activities, On-site operations, and Off-site manufacturing and construction [2]. In recent years, driven by the wave of digitalisation, digital tools have become well established within construction firms and have only more recently begun to extend to construction sites, where their adoption remains less advanced than in previous construction phases. The concept of a digital construction site is emerging as an alternative to traditional practices, in which technologies such as Building Information Modelling (BIM), the Internet of Things (IoT), platforms, and Artificial Intelligence (AI) enable more efficient organisation and a highly interconnected workforce [3].

The AEC sector is characterised by high fragmentation and limited interoperability, stemming from the volume, diversity, and distributed nature of data produced throughout the building lifecycle. These challenges are compounded by the organisational complexity of construction companies and the wide range of actors, tools, and activities involved on construction sites. Moreover, the lack of standardised tools, procedures, and methodologies impedes effective information exchange, negatively affecting efficiency and quality. As a result, interoperability, defined as the ability of systems to share information and act on it, remains a critical challenge, often hindered by issues of data access, interpretation, or use across heterogeneous systems. Addressing this issue cannot rely on traditional operator-driven approaches; instead, it requires integrating diverse digital solutions. In this context, Information and Communication (IC) technologies are essential for reducing and potentially overcoming interoperability barriers. Among these, ontologies support data exchange, integration, and knowledge sharing across systems by enabling information retrieval from diverse sources [4, 5].

Improved digitalisation and interoperability in the AEC sector contributes to environmental sustainability by reducing resource consumption, enhancing social sustainability by improving working conditions, and facilitating effective construction project management [6]. Alongside digital solutions, automation technologies are increasingly central to both On-site and Off-site construction, enabling a shift from traditional site-based processes to controlled environments. These new approaches are driving the construction industry toward models already established in sectors such as automotive, industrial design, and shipbuilding, where subassemblies are preassembled off the main assembly line, producing high-quality, optimised, and specialised products [7].

Beyond technological innovation, the transformation of the construction sector is increasingly influenced by broader Environmental, Social, and Governance (ESG) sustainability considerations; these, combined with digital transformation, represent both a challenge and an opportunity [8] and offer a significant perspective for examining the contribution of digital solutions [9]. Growing regulations and investor demands require AEC firms to show measurable sustainability outcomes, including reductions in both operational and embodied carbon emissions, the promotion of inclusive and safe working environments, and improvements in transparency and accountability [10]. Digital tools such as BIM, IoT, and cloud computing facilitate these goals by enabling real-time monitoring and control of energy consumption, reducing operational carbon [11], and increasingly, by improving material quantification accuracy, optimising design, and supporting the integration of life-cycle assessment methods. Digital platforms also increase transparency and collaboration, resulting in productivity gains of up to 15% and cost savings of 4–6% [12], while supporting compliance with social commitments in tenders [13–15]. ESG-aligned practices are increasingly embedded in public procurement and private-sector contracts, making compliance vital for both ethics and market access.

This paper presents a review of digital transformation in the AEC industry through a Systematic Literature Review (SRL). Focusing on digital solutions for building projects and digital construction sites. The main research question is:

- *How has the adoption of digital solutions in the AEC sector evolved over the past decade with respect to technological typologies, application contexts, and integration potential?*

As the number of digital solutions grows, collaboration, efficiency, and data-driven decision-making across design, construction, and operations improve. However, the full potential of digital tools can only be realised through effective integration and data exchange across platforms, making interoperability crucial. Building on these considerations, this research further explores two related research questions:

- *What are the challenges and opportunities in integrating data across various digital technologies?*
- *How do current digital solutions exchange information among them, and what is their current level of development, application, and interoperability?*

The paper is structured as follows: Section 2 details the SLR methodology and literature selection criteria. Section 3 presents the review results, combining bibliometric and thematic analyses across the identified digital solutions. Section

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4 discusses the findings in relation to the research questions, and Section 5 reports the conclusions.

2. Methodology

This work relies on an SLR, conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol [16], ensuring a scientific and transparent process that aims to minimise biases associated with selective reporting of results and discretionary decisions in the collection and utilisation of data from primary research. This protocol provides a roadmap to conduct an SLR, following four main steps: i) identification, ii) screening, iii) eligibility and iv) inclusion. The entire review process is shown in Figure 1. To provide comprehensive coverage of the digital technologies applied in the AEC sector, the authors conducted the identification phase by querying two internationally recognised multidisciplinary databases: Scopus and Web of Science.

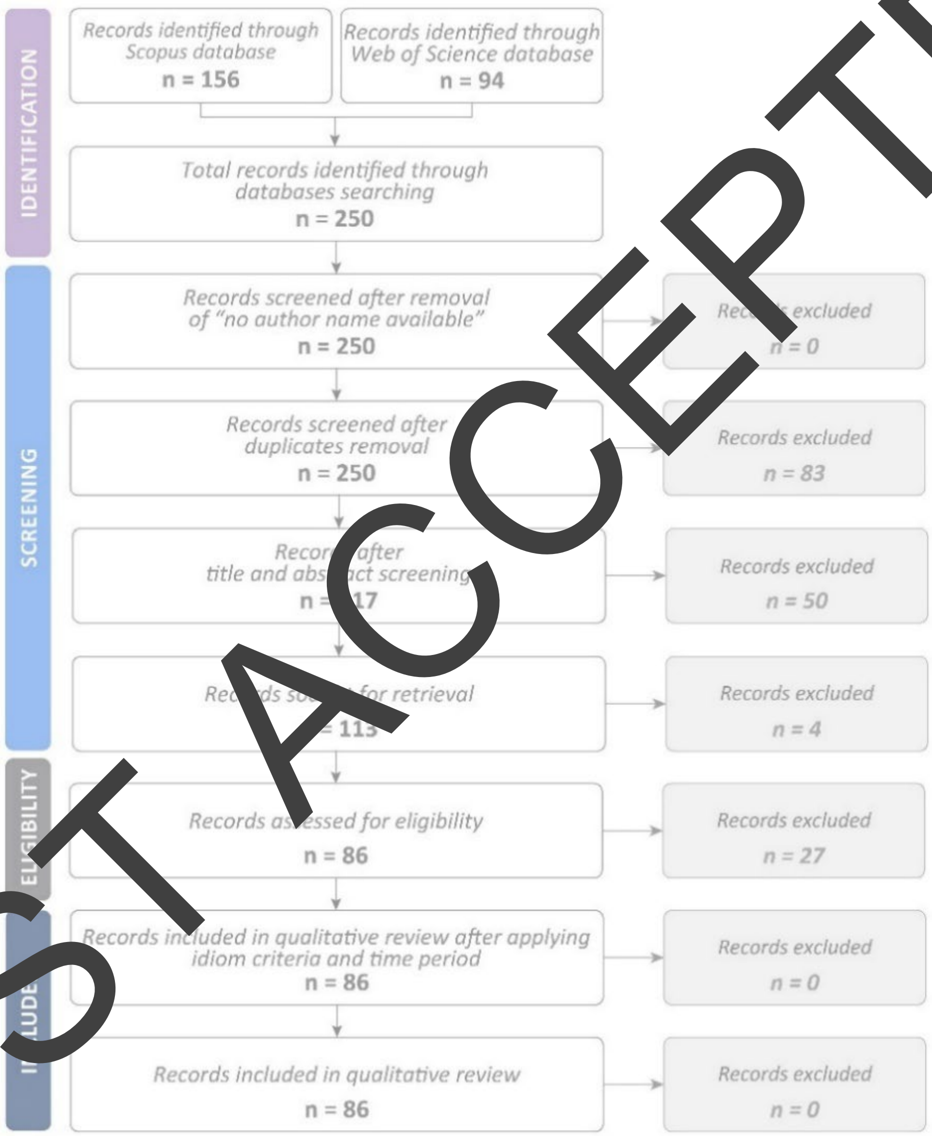

Figure 1 – PRISMA flow diagram synthesising the identification, screening, eligibility and inclusion phase conducted for the present study.

The research was performed in the "Article title/Abstract/Keyword" field using a string combining construction sites and various digital technologies. To ensure a thorough and systematic review, the final set of keywords was structured around three main elements: the first addresses the contextual domain, namely construction sites; the second focuses on the broader digitalisation domain; and the third targets specific digital technologies. Table 1 shows the final search string, time frame, and inclusion and exclusion criteria. During the exploratory phase of the search, alternative English spellings for some keywords were tested; since they did not yield additional results, only one consistent spelling for

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each term was retained in the final search string.

Table 1. Overview of the research protocol used to conduct the SLR, including research questions, search method, search string and inclusion and exclusion criteria adopted.

Aim of the study	To examine current studies on contemporary technologies applied in the AEC sector, with special attention to their integration, focusing on the interoperability aspect.	
Research questions	RQ 1	How has the adoption of digital solutions in the AEC sector evolved over the past decade with respect to technological typologies, application contexts, and integration potential?
	RQ 1.1	*What are the challenges and opportunities in integrating data across various digital solutions?*
	RQ 1.2	*How do current digital solutions exchange information among them, and what is their current level of development, application, and interoperability?*
Search method	Databases	Scopus, Web of Science
Search string	Keywords	TITLE-ABS-KEY ("Construction site*" OR "Construction area" OR "Work site" OR "Building site" OR "construction process") AND TITLE-ABS-KEY ("Digital technolog*" OR "Digitalization" OR "Digital Transformation" OR "Digitization" OR "Digital fabrication") AND TITLE-ABS-KEY ("robotics" OR "robotic technologies" OR "construction robots" OR "autonomous robots" OR "robotization" OR "mobile manipulator" OR "mobile robot" OR "UAVs" OR "Automated guided vehicle" OR "drones" OR "monitoring technolog*" OR "visual data acquisition" OR "internet of things" OR "smart sensor" OR "UAVs" OR "automated monitoring" OR "machine learning" OR "BIM" OR "Building Information Modelling" OR "Information management" OR "GIS" OR "Geographic Information System" OR "surveying technologies" OR "surveying tools" OR "3D modelling" OR "surveying" OR "Survey* instruments" OR "Survey* devices" OR "Survey* tools" OR "progress monitoring" OR "3D scanning" OR "laser scanning" OR "drones" OR "photogrammetry" OR "off-site" OR "prefab*" OR "modular" OR "MMC" OR "extended reality" OR "augmented reality" OR "virtual reality" OR "mixed reality")
	Year	2014-2024
	Subject Area	Engineering
	Document	Journal articles, review articles, conference papers and chapters
	Language	English
Review method	Data extraction	Excel sheets to check papers, authors, and features based on the inclusion criteria
Exclusion criteria	• Outside the time period 2014-2024 • Full article not available for download • Studies not written in the defined idiom • Studies not related to building construction, such as those focusing on infrastructure construction (e.g., roads, bridges, tunnels) or other non-building construction processes.	
Inclusion criteria	• Studies published within the time period 2014–2024 • Journal articles, review articles, conference papers and chapters with full-text availability • Studies specifically related to building construction sites • Studies in which digital solutions represent a central and predominant focus, rather than a peripheral or contextual element	

The identification phase yielded 250 publications, including journal articles, conference articles, and book chapters. After removing duplicates and records lacking author information, 167 publications remained. A preliminary screening of titles and abstracts was then conducted to ensure alignment with the research objectives and to exclude studies not directly related to building construction (i.e., infrastructure studies) or those that included the search keywords without substantive relevance. This screening step reduced the sample to 117 publications. Whenever possible, the full texts were retrieved from the databases used in our search and from institutional or open-access repositories. When the full texts could not be accessed through any of these means, the paper was excluded from the analysis. The remaining full-text articles were thoroughly reviewed to determine eligibility for final inclusion in the systematic review. Of 86 publications, all met the inclusion criteria and were selected for qualitative analysis.

A publication year filter was applied, restricting the literature review to studies published between 2014 and 2024. The year 2014 was selected as a reasonable starting point for the investigation, as scholarly discussions about the digital

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transformation of construction sites had advanced over the previous decade.

3. Results

3.1 Bibliometric Analysis

To support the qualitative review process, a bibliometric analysis was conducted at the end of the screening phase to assess the influence and distribution of the publications, providing a quantitative characterisation of the structure and dynamics of the research field [17, 18]. The temporal distribution of scientific production (Fig. 2a) illustrates a clear evolution over the past decade. From 2014 to 2020, the number of publications remained relatively limited, but beginning in 2021, an almost exponential growth was observed, culminating in more than 20 contributions in 2024. The trend reflects rising interest in digital construction, likely driven by broader adoption of BIM, IoT, and related tools, the industry's digital transformation and the post-pandemic shift towards automation and remote monitoring.

Since 2020, review articles on the topic have increased, accounting for 16.3% of the total publications included, reflecting efforts to consolidate and critically assess knowledge in this field. Despite the expanding body of literature, the publication landscape remains highly dispersed: only 5 sources published more than 3 articles over the past decade (Fig. 2b), with approximately 60% of the journals contributing only 1 or 2 articles, underscoring the discipline's emerging nature and the absence of a consolidated core of reference journals. Most publications appear in Buildings (11) and Sustainability (8). The contributions of specialised journals such as Automation in Construction and Applied Sciences demonstrate the growing maturity and interdisciplinary engagement in the domain.

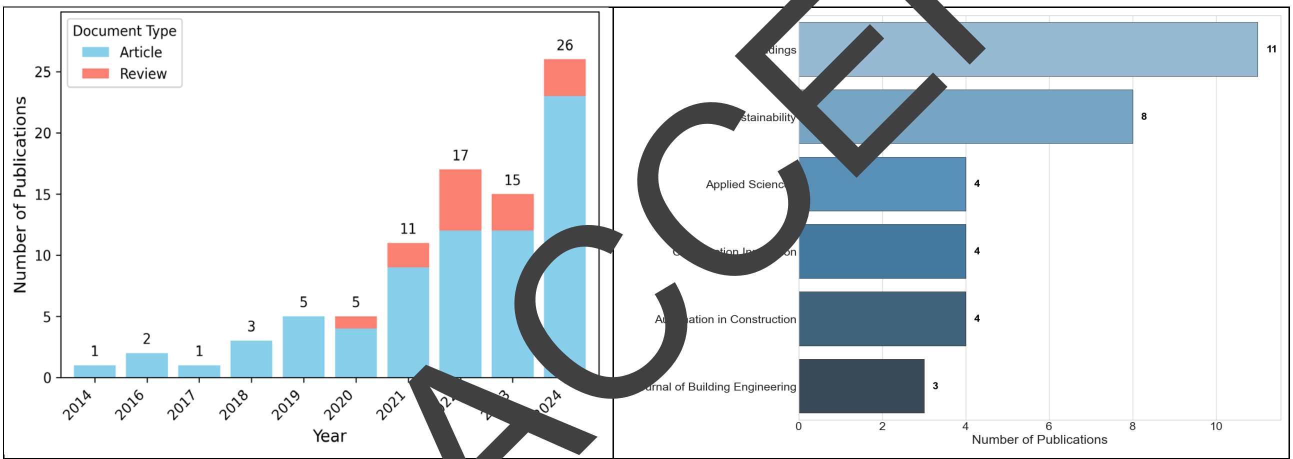

Figure 2 – (a) Annual scientific production related to digital construction from 2014 to 2024; (b) Most relevant scientific sources by number of publications.

To investigate thematic convergence among the selected papers, a co-occurrence analysis of the authors' keywords was conducted using VOSviewer. To ensure consistency and avoid semantic redundancy, a thesaurus was developed to normalise items and merge keyword variants (e.g., "BIM", "Building Information Modelling", "BIM modelling"). As a result, "Building Information Modelling" emerged as the most frequently used keyword, followed by "digitalisation", "Internet of Things", "project management", and "augmented reality". The keyword co-occurrence network (Fig. 3) highlights six distinct thematic clusters, each shown in a different colour. This clustering provides an overview of themes and interrelationships within the analysed literature. Building on this analysis, the identified clusters were used to support the authors in a structured categorisation of digital solutions into three main groups: (i) Data Acquisition solutions, (ii) Digital Fabrication and Automation solutions, and (iii) Digital Information solutions.

In the co-occurrence network of author keywords, several terms emerge from the red cluster, adjacent to parts of the yellow cluster: "drone", "object detection", "construction management", "digital twin", and "Internet of Things". These keywords clearly emphasise data-collection technologies, thereby enabling the authors to identify the first category of digital solutions: "Data Acquisition Solutions". The yellow and blue clusters feature keywords such as "Internet of Things", "smart construction", "prefabricated buildings", "digitalisation", "automation", and "prefabrication", indicating research concerned with automated systems and advanced fabrication techniques. These contributions address both On-site and Off-site settings, highlighting the role of automation. These were grouped into a second category, named "Digital Fabrication and Automation Solutions". The purple, light blue, and green clusters include keywords like "building information modelling", "artificial neural network", "information management", "project management", "augmented reality", "virtual reality", and "computer vision". These focus on structured information,

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digital workflows, and immersive visualisation, forming the third category: "Digital Information Solutions".

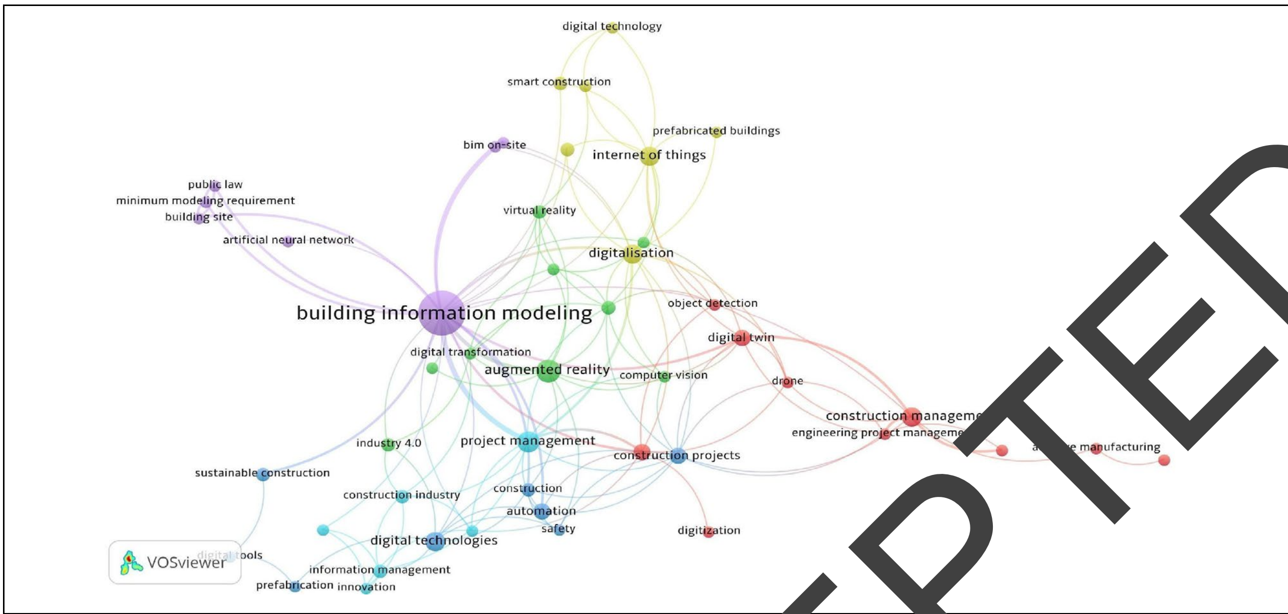

Figure 3 – Visualisation of the co-occurrence network of author keywords generated using VOSviewer. The map illustrates relationships among keywords that co-occur at least twice in the selected documents.

The Global Country Map (Fig. 4) shows a dense concentration of publications across European nations, particularly the United Kingdom, Germany, and Italy, as well as China, Australia, and the United States. Among these, the United States, Italy, Germany, and China emerge as central hubs. Overall, the bibliometric analysis confirms the growing interest in digital construction, with a notable acceleration in scientific production over the last five years.

The research landscape is diverse yet fragmented, marked by a growing number of journals, the dominance of keywords related to BIM and emerging technologies, and an extensive international research network. These patterns highlight the need for a more critical understanding of how digital solutions are applied and integrated within construction workflows. Building on this insight, the following section moves beyond bibliometric trends to a structured analysis of the identified digital solutions.

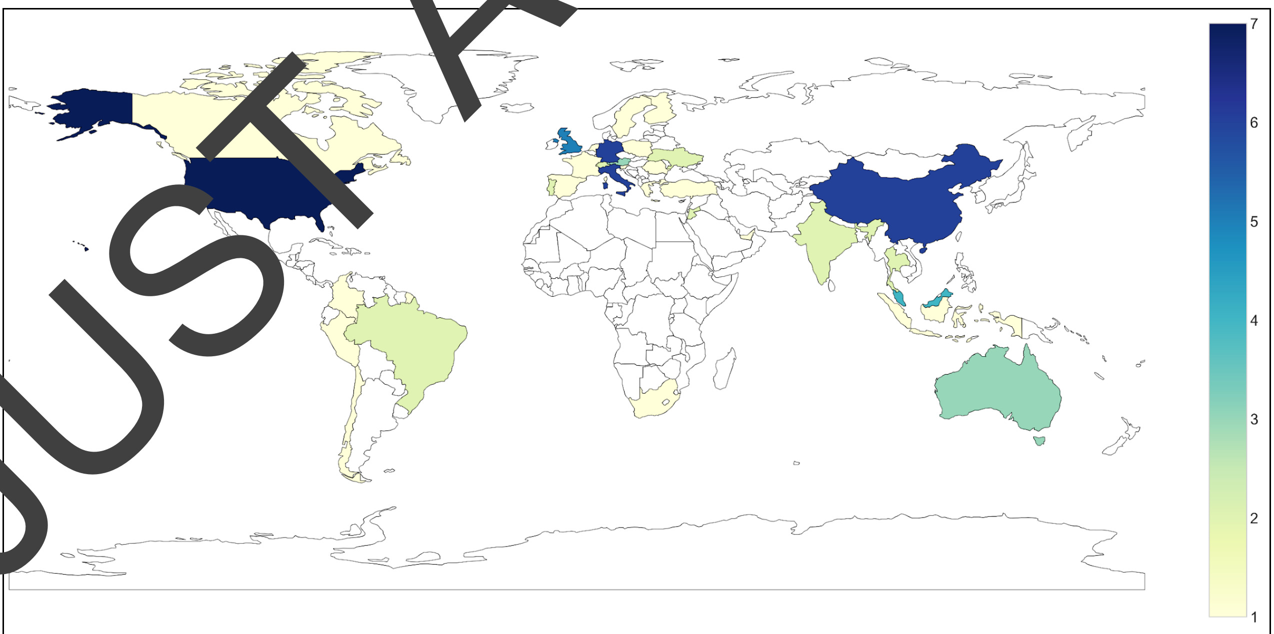

Figure 4 – Number of publications by country based on the bibliometric analysis.

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3.2 Thematic Analysis of Selected Articles

This section discusses the research findings and analyses the digital solution landscape that emerged from the SLR. Digital solutions were categorised into thematic clusters based on keyword co-occurrence analysis, reflecting current research patterns. As illustrated in Figure 5, two levels of categorisation have been identified. At the first level, the thematic clustering led to the identification of three main groups of digital solutions: (i) Data Acquisition solutions, (ii) Digital Fabrication and Automation solutions, and (iii) Digital Information solutions. At the second level, these groups were further divided into subcategories, yielding six types of digital solutions: Surveying, Monitoring, On-site automation, Off-site automation, Information modelling, and Extended Reality solutions.

Figure 5 – Categorisation of six digital solutions identified in the literature, structured into three main categories.

From the SLR elaboration, a definition was assigned to each of the three categories and the related digital solution:

- **Data Acquisition solutions** are methods, processes, technologies, and integrated systems aimed at systematically collecting and pre-processing spatial, environmental, and operational data throughout the construction lifecycle. These include surveying and monitoring technologies to provide high-quality input for data-driven analysis—ranging from rule-based and statistical methods to advanced AI-based approaches—to support real-time or near-real-time decision-making, safety compliance, and construction performance.
  - Surveying solutions: advanced tools and methodologies used to acquire, process, and interpret spatial data, creating high-resolution 3D models of both built and natural environments. Technologies include Unmanned Aircraft Systems (UAS), Terrestrial Laser Scanners (TLS), and photogrammetric techniques (SfM, MVS) to generate point clouds, Digital Terrain Models (DTMs), Digital Surface Models (DSMs), and orthoimages with centimetre accuracy. These facilitate real-time comparison of as-planned and as-built conditions throughout all construction phases [?–23].
  - Monitoring solutions: integrated digital systems that collect, process, and analyse real-time construction site data to support decision-making, ensure safety, and improve efficiency. They use IoT sensors, wearables, Computer Vision (CV), Unmanned Aerial Vehicles (UAVs), and cloud platforms to continuously monitor workers, equipment, and site conditions. Applications include safety management, progress tracking, and anomaly detection. Integration with BIM, Geographic Information System (GIS), and project management tools enables dynamic risk assessment, real-time dashboards, and automated reporting [24–28].

- **Digital Fabrication and Automation solutions** comprise a set of data-driven processes and technologies that, either directly or indirectly, impact the construction site by enhancing both On-site and Off-site construction (OSC). Utilising advanced machinery, automated systems, and integrated workflows, digital transformation in the AEC sector has enabled precise control over fabrication technologies and increased efficiency from design to execution. These developments have significantly improved productivity, accuracy, and coordination across the construction lifecycle.
  - On-site automation solutions encompass key procedures, methodologies, and technologies aimed at automating the construction site, as opposed to Off-site automation solutions using stationary machines. This approach often employs mobile systems, enabling the continuous production of even complex structures and eliminating the need to transport bulky components produced Off-site. They can operate in dynamic environments and are suitable for both new construction and building renovation [29–33].
  - Off-site automation solutions, traditionally referred to as prefabrication, involve manufacturing or assembly of building components in factories for later installation on the construction site [34]. These workflows are streamlined by digitalisation and automation solutions [35]. Digitalisation optimises design-to-manufacturing pipelines by enabling coordination and performance monitoring, while automation reduces human effort, enhances production processes, and automates complex tasks using robotics and machinery.

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- **Digital Information solutions** refer to a set of technological tools and systems for efficient creation, management, and exchange of digital data across the construction project lifecycle. These include BIM, Common Data Environment (CDE), Digital Twin (DT), and construction management platforms, often integrated by IoT sensors, reality capture methods, and mobile or immersive applications. They enable real-time collaboration, improve planning and execution, and support data-driven decisions, enhancing productivity, reducing costs, and minimising errors. These solutions facilitate a seamless transition between construction phases and operational management, fostering lifecycle-oriented practices and driving more integrated, transparent, and efficient construction processes that align with sustainability, safety, and technological innovation.
    - Information Modelling solutions aim to manage project and construction data, enhancing collaboration and information exchange among stakeholders [36], often within a CDE [37]. BIM, a digital representation of a facility's physical and functional characteristics [38], has emerged as a key digital methodology enabling efficient, integrated, and data-driven management of construction processes [39]. Initially an extension of 2D to 3D modelling, BIM now incorporates additional dimensions: time (4D), cost management (5D), sustainability (6D), facility management (7D), and safety (8D) [40]. In recent years, a shift from BIM to DT has further enhanced building management with real-time data and interoperability.
    - Extended Reality solutions (XR) encompass methodologies, procedures, and immersive technologies, i.e., Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), that merge physical and digital environments to enhance interaction, visualisation, and decision-making. In construction safety and management, XR enables users to engage with virtual or augmented content via head-mounted displays or mobile devices, creating context-rich environments that replicate or augment real-world settings. VR offers fully simulated environments, enabling workers to explore job site scenarios in a risk-free context, ideal for hazard recognition and training. AR overlays digital models and information onto the real world, enabling real-time inspection, assembly, and hazard identification. MR enables dynamic interaction between physical and virtual objects, anchored in real-world coordinates, thereby enhancing spatial fidelity. Integration with BIM and GIS enhances training and safety applications, visual planning, and lifecycle insights. When combined with deep learning, XR delivers context-aware feedback, real-time hazard detection, and adaptive guidance, serving as an educational and operational tool to enhance safety, decision-making, and collaboration [41–44].

3.2.1 Data Acquisition Solutions

Data Acquisition solutions enable the digital transformation of construction sites, offering insights into how digital tools can enhance project execution and safety while promoting a more connected, data-driven construction process. The following paragraphs examine the literature clustered in this category by focusing on the two main digital solutions identified: surveying and monitoring.

3.2.1.1 Surveying Solutions

Digital surveying solutions address the limitations of traditional manual methods (e.g. tape measurements, total stations, and theodolites) by enabling efficient, automated, and data-driven acquisition of spatial information. These technologies have improved the accuracy of geometric modelling, the reliability of site documentation, and the ability to support real-time project decisions. Advancements in this field include integrating VR with automated surveying tools. Saleh et al. demonstrated that UAV-based image acquisition, combined with BIM and VR visualisation, can enhance spatial analysis, logistical acquisition, and progress tracking [19]. The resulting DTs facilitate intuitive comparisons between the as-built and the design intent, thereby enhancing transparency in decision-making. However, such applications require substantial technological infrastructure, consistent procedures during system setup, and standardised processes and accessible interfaces [19].

In image-based surveying, Ekanayake et al. introduced an optimised Mask R-CNN model specifically adapted for indoor environments, where traditional surveying techniques are often less effective [20]. Their approach automates the detection of key construction elements, such as insulation and drywall, from UAV-acquired images, with the results integrated into an interactive dashboard. The system achieved a mean average precision of 88.02%, demonstrating effectiveness even in low-light and occluded scenarios. Nevertheless, the study cautions that broader generalisation may require more diverse training data [20].

To address inefficiencies in conventional surveying workflows, Torres et al. proposed a comprehensive system architecture that integrates photogrammetry, IoT, and BIM within a Building DT framework [21]. Their research redefines surveying as a continuous, cross-functional activity embedded within site intelligence. The digital workflows in this framework are formalised using Business Process Model and Notation 2.0 (BPMN 2.0), a standardised graphical

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notation for modelling business processes that promotes interoperability across stakeholders and systems. This approach structures the representation of tasks, events, and decision gateways, facilitating automation and coordination of complex construction processes. BPMN 2.0-based workflows allow dynamic updates of safety, quality, and productivity metrics. Besides the lack of field validation, the study offers a valuable model for how surveying data can drive proactive site management [21].

The quality and suitability of datasets used in digital surveying were examined by Qureshi et al., who conducted a comparative benchmarking study of 12 photogrammetric platforms using construction-specific datasets [22]. The evaluation included metrics such as Cloud-to-Cloud (C2C), completion percentage, and Multiscale Model-to-Model Cloud Comparison (M3C2). Their analysis identified five key environmental parameters that influence the performance of image-based surveying. The study emphasised that data quantity alone is insufficient; context-aware data collection strategies and proper evaluation frameworks are essential for accurate reconstructions [22].

Focusing on UAV-based topographic surveying, Cho et al. developed a robust workflow for digitising large-scale earthworks [23]. Their methodology integrates high-precision ground control points (GCPs), photogrammetric reconstruction, and Python-based automation for tasks such as volume calculation and terrain monitoring. The resulting system achieved sub-3 cm accuracy and produced outputs such as height-differential maps and safety zones. However, its scalability is currently limited by the need to manually filter out moving objects, such as workers and machinery, that disrupt the accuracy of point clouds. The authors also noted the importance of enhancing georeferencing practices by deploying denser GCP networks [23].

In summary, the reviewed contributions underline how digital surveying solutions, spanning UAV photogrammetry, AI-based image analysis, VR integration, and DTs, are reshaping the construction landscape. These technologies not only enhance geometric documentation but also enable real-time monitoring, predictive analytics, and decision support. Despite their promise, widespread adoption requires addressing key challenges, including usability, interoperability, dataset quality, and field-level adaptability.

Table 2. Summary of the analysis of Surveying solutions, reporting improvement levels, application areas, and the main benefits and challenges identified in the literature.

	Tot. Articles	**Identified articles**
Surveying solutions	5	[19, 23]
Topic	**Typology**	**Reference**
Improvement level	• Enabling improvement	[19, 23]
	• Qualitative improvement	[19, 22, 23]
	• Quantitative improvement	[19, 22, 23]
	• Safety improvement	[19–21]
Application areas	• Project planning and design	[19, 23]
	• Project management	[19, 21, 23]
	• Health and safety	[19–21]
	• On-site operation, logistics and supply chain	[19, 23]
	• Construction methods	[19, 22, 23]
	• Structural health assessment	---
Benefits	• High-precision data acquisition	[19, 22, 23]
	• Remote inspection improves safety	[19–21]
	• BIM integration for as-built validation	[19, 23]
	• Informed planning and logistics decisions	[19, 23]
	• Efficient documentation	[19, 22]
	• Applicable to complex environments	[22, 23]
Challenges	• Variable accuracy in harsh conditions	[19, 23]
	• Skilled personnel required	[20, 22]
	• Need for ground control points	[23]
	• Large data processing burden	[22]
	• High equipment/software costs	[19, 22]
	• Limited interoperability without standards	[19, 21]

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3.2.1.2 Monitoring Solutions

Digital monitoring solutions, ranging from CV systems to IoT, wearable sensors, and UAS, are increasingly adopted to enable real-time observation, automated data collection, and hazard detection, thereby supporting more effective site supervision and risk mitigation. CV techniques have shown significant potential in enhancing health and safety monitoring. They involve applying AI-driven image and video analysis to automate the observation, documentation, and assessment of construction activities. These methods enhance traditional manual processes by providing real-time data extraction, object recognition, and operational insights, enabling efficient project management and safety compliance [45–47]. According to Arshad et al., CV systems can detect critical safety events, such as improper use of Personal Protective Equipment (PPE) and fall-risk situations, using advanced image-based techniques, including multi-object tracking [24]. Multi-object tracking algorithms monitor workers, equipment, and materials across sequential frames to analyse spatial interactions and workflows [46].

A YOLO (You Only Look at Once)- based model achieved up to 96% accuracy in PPE detection when integrated with semantic ontologies [48]. Despite their effectiveness, Arshad et al. highlight limitations arising from dataset bias, regulatory constraints, and the dynamic, unpredictable nature of construction environments, which can compromise the reliability of automated monitoring solutions [24]. The study also compares CV with IoT systems, highlighting the latter's strengths in automation and real-time tracking but noting issues such as hardware dependency and energy efficiency. The authors advocate hybrid solutions that combine CV and IoT to enable multimodal safety analytics [24].

Table 3. Summary of the analysis of Monitoring solutions, reporting improvement levels, application areas, and the main benefits and challenges identified in the literature.

	Tot. Articles	**Identified articles**
Monitoring solutions	5	[24–28]
Topic	**Typology**	**Reference**
Improvement level	• Enabling improvement	[25, 27, 28]
	• Qualitative improvement	[24–26]
	• Quantitative improvement	[24, 27]
	• Safety improvement	[24–26]
Application areas	• Project planning and design	---
	• Project management	[27, 28]
	• Health and safety	[24–26]
	• On-site operations, logistics and supply chain	[25, 27]
	• Construction methods	[25, 27]
	• Structural health assessment	[26]
Benefits	• Automated safety and compliance control	[24–26]
	• Real-time tracking of workers and equipment	[25, 27]
	• Early detection of risks and anomalies	[24, 25]
	• BIM and DT integration	[27, 28]
	• Reduced inspection time	[27]
	• Improved PPE usage detection	[25, 26]
	• Accident prevention support	[24–26]
Challenges	• Cultural resistance to digital tools	[24, 25]
	• High initial costs	[26, 27]
	• Integration challenges with existing systems	[27, 28]
	• Data protection and privacy issues	[25, 26]
	• Lack of standardisation	[28]
	• Operational reliability in harsh environments	[27]

In addition to technical aspects, inspection and control activities have also benefited from digitalisation. Rey et al. present the "Smart Inspects" system, which integrates digital safety checklists with drone-based inspections to enhance task coordination and reduce inefficiencies [27]. Deployed in 55 weekly inspections across two construction sites in Brazil, the system achieved a 73% reduction in inspection time and improved the detection of non-conformities.

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However, its applicability is partially constrained by environmental conditions, such as weather and indoor-use constraints. The study emphasises the importance of aligning such tools with standardised procedures to ensure broader scalability and effectiveness [27].

Beyond technological capabilities, several studies have examined the procedural challenges that hinder the adoption of monitoring solutions. Tabatabaee et al., using the Fuzzy Delphi Method (an advanced consensus-building technique that combines the classical Delphi method with fuzzy set theory to systematically gather and quantify expert opinions, especially when dealing with uncertainty and subjective judgments) [49], identified and prioritised 18 barriers to IoT implementation in safety monitoring [25]. Their findings, drawn from the Hong Kong construction context, reveal widespread concerns, including productivity losses, training burdens, privacy issues, and general scepticism regarding the reliability of technology. Insufficient policy support and limited digital competencies among workers compound these barriers. Although regionally focused, the study offers a valuable taxonomy of obstacles and underscores integrative strategies that combine innovation with workforce training and change management [25].

From a regional and policy-driven perspective, Ibrahim et al. [28] examine IoT adoption in Malaysia's construction sector, finding uneven diffusion of tools such as BIM, Radio-Frequency Identification (RFID) systems, and smart sensors. UAVs and communication platforms are increasingly used, but sensor-based health monitoring remains constrained by cost and training barriers. The study highlights the interplay between government-led BIM initiatives and digital transformation efforts, while acknowledging its descriptive scope and limited empirical depth [28].

A broader overview is offered by Maali et al., who conducted a systematic review of digital safety technologies [26]. The study categorises these into four strategic domains: prevention through design, safety management, safety culture, and computational applications. Sensing devices (28.7%) and AI-based vision systems (21.7%) are the most used tools for real-time monitoring, ergonomic support, and behavioural analytics. The authors also developed a practical checklist that links technologies to specific safety goals, serving as a decision-support tool for practitioners. However, the study's descriptive nature and limited focus on ethical implications represent key limitations [26].

In summary, the reviewed contributions converge on the strategic role of monitoring solutions in advancing digital safety on construction sites. While the integration of CV, IoT, and other digital tools has demonstrated tangible benefits, widespread adoption is still constrained by technical, organisational, and socio-regulatory barriers. These findings reinforce the need for comprehensive, cross-disciplinary strategies that couple technological innovation with policy reform, standardisation, and workforce upskilling.

3.2.2 Digital Fabrication and Automation Solutions

The literature distinguishes two domains: On-site and Off-site. The use of digital solutions in OSC is well documented across all phases of the construction process, from design and manufacturing to transportation and On-site assembly [50, 51]. While a growing body of research supports their application in Off-site processes, the authors also aim to examine in detail the emerging, digitally driven, and automated innovations On-site. Accordingly, the next subsections provide an overview of the digital and automation solutions applied in the two domains.

3.2.2.1 Off-site Automation solutions

Among the reviewed literature, two key studies map the spectrum of digital solutions in OSC. Olawumi et al. [51] focus on the modular integrated construction method and identify digital technologies across the construction process – manufacturing, transportation, and On-site assembly – highlighting the use of BIM, simulation tools, AR, CV, and RFID systems to automate production data collection. Following a similar approach, Gutiérrez et al. [50] narrow their scope to the timber industry, regarded as one of the most advanced sectors in Off-site processes and in the level of prefabrication of building components. In their study, the authors highlight that the timber industry is driven by rapid advances in automated fabrication processes, including robotic systems for manufacturing timber products and components. While the pivotal role of digital technologies in the timber industry is widely acknowledged, the authors highlight the lack of their systematic integration into existing automated fabrication processes, which is essential for scaling up timber-based OSC, thereby improving productivity and further enhancing process sustainability [50].

To address interoperability and systemic integration challenges, one emerging field explores the role of blockchain technology, when combined with BIM, machine learning, RFID, and IoT, as a promising enabler of data traceability, information security, and decentralised information management in OSC [51].

Further advancing the discussion on interoperability issues among digital and automation systems, Lei et al. [35] identified inefficiencies arising from information loss throughout the OSC process. Drawing on a case study of a timber panel manufacturer, the authors suggest a shift from off-the-shelf tools to customised digital solutions, for instance, using open Application Programming Interfaces (APIs) to enhance integration between BIM, Enterprise Resource Planning, and Computer-Aided Design and Computer-Aided Manufacturing systems (CAD/CAM), reducing labour costs due to data loss and duplication.

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The reviewed studies cover all phases of the OSC process, from design to On-site assembly. Although the primary focus of this paragraph is to examine digital and automation solutions in the manufacturing phase and, consequently, their role in reshaping On-site operations through Off-site components, it is necessary to address the design phase as well. Most Off-site production processes rely on CAD/CAM systems that translate design information into the machine language required by industrial equipment. Given the complexity and level of detail required in OSC, one research line focuses on automating and semi-automating the design process. For instance, the potential of generative algorithms and BIM to enhance production efficiency and sustainability is highlighted in the literature [52].

Table 4. Summary of the analysis of Off-site automation solutions, reporting improvement levels, application areas, and the main benefits and challenges identified in the literature.

	Tot. Articles	**Identified articles**
Off-site automation solutions	11	[35, 50–59]
Topic	**Typology**	**Reference**
Improvement level	• Enabling improvement	[51–53, 55, 56, 59]
	• Qualitative improvement	[35, 51, 52, 57]
	• Quantitative improvement	[52, 54, 56]
	• Safety improvement	[51, 58]
Application areas	• Project planning and design	[50, 52, 56, 57]
	• Project management	[57, 58]
	• Health and safety	---
	• On-site operation, logistics and supply chain	[35, 51, 57–59]
	• Construction methods	[53–56]
	• Structural health assessment	---
Benefits	• Facilitation of integrated workflows from design to production	[35, 52, 53, 55, 56]
	• Enhanced manufacturing precision	[52–55]
	• Increased productivity and production process standardisation	[50, 52, 56]
	• Material optimisation	[53, 55, 56]
	• Realisation of complex geometries and high component customisation	[53, 54]
	• Real-time production monitoring systems	[53, 57–59]
Challenges	• Lack of systemic integration between digital design tools and automated processes, data fragmentation, and data duplication between the design and production	[35, 50]
	• The workflow community needs the implementation of open standards and APIs	[35]
	• Limitations of off-the-shelf software often require the development of customised solutions from manufacturers tailored to the specific needs	[35]
	• Broader adoption of digital solutions depends on the concurrent implementation of automation technologies	[50]
	• Ensuring consistent quality across all the OSC process phases is challenged by the poor communication between stakeholders	[57, 58]
	• Reverse supply chains are fragmented and lack coordination	[50, 51]
	• Verifying component identity and material compliance on the construction site	[57, 58]

Design-stage automation can streamline the manufacturing of complex components through integrated workflows. Studies show the benefits of such approaches in articulated timber and concrete structures. Yuan et al. [53] describe a shell timber structure utilising reciprocal geometries, parametric design, and shape optimisation. The sophisticated production process relies on automated 7-axis robots and supervisory software, which employ a DT to simulate and correct errors. The structure's envelope has been completed with 3D-printed plastic panels tailored to its curvature, demonstrating the potential of combining robotic arm, DT, and additive manufacturing for high-precision components.

Beyond timber, material optimisation is mainly critical for heavy Off-site components, such as concrete ones. Ma et

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al. [54] used topological optimisation to improve material distribution in precast ribbed slabs, creating recyclable, reusable formwork inspired by Nervi's structural designs. The study employs a hybrid digital fabrication process that combines robotic 3D printing for complex geometries with Computer Numerical Control machining for flat surfaces.

Other studies [55] have implemented digital solutions in concrete-based prefabricated envelope systems, integrating multifunctional design and 3D printing to combine thermal insulation, structural performance, and space for building services, offering a comprehensive construction solution within a single element.

Towards resource-efficient production, digital and automation solutions are also applied at the interface between design and manufacture. Esenarro et al. [56] developed an advanced nesting process using a Grasshopper algorithm to optimise the laser cutting of modular components, reducing material waste by 20% and fabrication costs by 28% compared with conventional methods.

Off-site building components, despite their quality, can be damaged during transport and handling, which can affect installation and performance. Piaia et al. [57] address this by combining RFID or QR codes identification with thermal and laser scanning for early defect detection and performance monitoring throughout the construction process. Similarly, Wang et al. [58] introduce an intelligent construction system for prefabricated buildings, a digital platform that coordinates all phases of the OSC process by integrating BIM, RFID, sensors, IoT, and AI. By tracking components from manufacturing to installation, the system allows real-time corrective actions and synchronises products with their DTs, supporting long-term maintenance, quality control, and lifecycle management.

3.2.2.2 On-site automation solutions

Robotic technologies are a key driver of digitalisation in AEC, going far beyond the automation of repetitive tasks. Their integration with digital tools such as BIM [31, 60, 61] and CAD/CAM systems is reshaping the entire project lifecycle, from design through execution to management [60]. Digital models have evolved from simple virtual representations to operational platforms that direct robotics On-site and Off-site [62, 63]. Pioneer projects demonstrate how robotics enables full-scale construction with high precision and geometric complexity [64], supporting the shift from manual, sequential processes to automated, parallel, and data-driven workflows [62]. Robotics in AEC is diverse and measurable, boosting productivity and efficiency [31, 33, 65], operating continuously under harsh conditions, and performing tasks faster and with higher accuracy than humans [30]. They enhance quality by minimising human error and improving compliance with design specifications [62, 63] while reducing material waste and rework [61, 65]. A major advantage is improved safety, as robots automate dangerous or physically demanding tasks, thereby reducing workers' exposure to risk [30, 31, 61], enhancing efficiency, precision [33, 63].

A major frontier is On-site digital fabrication, especially 3D printing [32]. Mobile Additive Manufacturing (MAM) systems use mobile robots with multi-degree-of-freedom arms to extrude material directly on construction sites. These systems operate using strategies such as "print-while-driving" or "print-drive-print" and are adaptable to both new construction and renovation. Mobility is achieved via ground-based platforms or climbing mechanisms for scalable deployment [66]. The CONPrint3D system, developed at TU Dresden, converts concrete pump trucks into large-scale manipulators capable of printing monolithic concrete structures. While effective for standard geometries, challenges remain in maintaining material flow and compensating for the boom arm's dynamic behaviour [32, 65].

Although traditional industrial robots provide high precision, their limited range restricts their application. This can be addressed by integrating gantry systems, mobile platforms, or cable-driven systems, albeit at the expense of increased demands on positioning accuracy and structural infrastructure [65]. Innovations are not limited to concrete; robotic systems for wood fabrication are also under development, enabling the production of complex geometries [64].

In masonry, robotic bricklaying solutions such as the Mobile Robotic Bricklaying System (RBS) from Poland, which integrates an ABB robot on a tracked frame, are being deployed to construct walls across various building types [60]. Semi-Automatic Mason (SAM) uses sensors and lasers for precise wall tracking and brick placement, enhancing mason productivity [60]. The Automated Bricklaying Robot (ABLR), designed for flexibility, handles diverse brick types and excels at challenging geometries like arches and corners [60]. Additional robotic systems are adopted for finishing and structural assembly: robotic plastering and painting improve surface quality and reduce worker strain while automated welding robots provide precise, repeatable welds on steel structures, especially for complex joints [60].

Robots are increasingly used in off-site manufacturing to streamline modular component production and enable additive manufacturing of large-scale elements [67]. Material handling is also being transformed; robots and wearable exoskeletons assist with lifting and transporting heavy loads, improving safety and operational efficiency [60, 67].

For excavation, autonomous systems equipped with Real-Time Kinematic (RTK)-enhanced Global Navigation Satellite Systems (GNSS), IMUs (Inertial Measurement Units) and InfraBIM models can increase accuracy and optimise planning. These systems are valuable at hazardous or remote sites, improving safety, fuel efficiency, and productivity. Remote-control functions add flexibility [30, 33]. BIM integration enables more precise planning [31, 60] and real-time data collection via robotic monitoring [62], reducing execution times. Studies show a reduction of

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construction times for tasks such as substation wall erection by 60–80% compared with traditional methods [62].

Table 5. Summary of the analysis of On-site automation solutions, reporting improvement levels, application areas, and the main benefits and challenges identified in the literature.

	Tot. Articles	**Identified articles**
On-site automation solutions	14	[29–33, 60–68]
Topic	**Typology**	**Reference**
Improvement level	• Enabling improvement	[61]
	• Qualitative improvement	[29, 65]
	• Quantitative improvement	[30, 31, 6[illegible]]
	• Safety improvement	[30, 33, 6[illegible]]
Application areas	• Project planning and design	---
	• Project management	---
	• Health and safety	[30, 31, 33, 60, 61, 65–67]
	• On-site operation, logistics and supply chain	[29–31, 33, 60, 62, 64–67]
	• Construction methods	[30, 31, 61, 62, 64–68]
	• Structural health assessment	---
Benefits	• Significant reduction in construction time (e.g., 60–80% for walls) and economic advantages	[60, 61, 65]
	• Improved accuracy and greater safety on construction sites	[30, 33, 60, 61, 66, 67]
	• Increased productivity and better information management (with tools like BIM and CDE)	[29–31, 60, 61, 65]
	• Greater design freedom and better visualisation enabled by digital fabrication (e.g., 3D printing)	[61, 64, 66]
	• Systems adapting to material and construction tolerances	[62, 63, 66]
	• Potential for environmental benefits (e.g., use of low-clinker materials or combined structure/insulation solutions)	[60, 63, 65]
	• Simplified operational processes and software, usable by non-specialists	[62, 64, 68]
Challenges	• Fragmented sector, reluctant to change, with a shortage of skilled labour and unclear digital strategies	[31, 33, 60, 67]
	• High technical complexity in developing systems that manage construction tolerances, reinforcement integration, on-site precision, and complex data flows	[32, 63–65]
	• Challenges related to the specific properties of printable materials (e.g., rheology, buildability, layer bonding, and anisotropy)	[32, 65]
	• Need to adapt to site variability (e.g., changing environmental and logistical conditions); robotic localisation and context awareness remain challenging	[29, 31, 33, 63, 66]
	• Cybersecurity risks are often overlooked in unstructured construction environments and interconnected systems	[33]

Despite its potential, robotics adoption faces several hurdles. High initial costs for procurement, deployment, and maintenance limit accessibility, especially for SMEs [65]. Workforce resistance and lack of specialised skills hinder progress [31, 33]. Project fragmentation, variable site conditions, and multiple stakeholders complicate standardisation. Technical challenges include material tolerance [62], accurate real-time localisation in dynamic environments [29, 33], and maintaining reliable internet connectivity at remote sites [33]. Cybersecurity concerns are increasing as machines, sensors, and networked systems become more interconnected. Historically, construction has neglected cybersecurity in unstructured environments, increasing risks [33]. Regulatory and standardisation challenges, such as specifying printable concrete, are evolving and may involve high compliance costs [32, 65].

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Robotics in AEC holds potential to address chronic industry challenges: low productivity [31, 63, 65], skilled labour shortages [30, 31, 65], and the need for sustainable practices [63, 68]. Research and development focus on cost-effective, easy-to-deploy systems that integrate with existing workflows [65]. Progress toward heterogeneous robotic fleets that dynamically collaborate with humans opens new frontiers [29, 63, 68]. AI and machine learning will allow robots to make autonomous decisions, optimise real-time workflows, and enhance quality [29, 68]. Innovations such as MAM with advanced materials (e.g., foamed concrete and mixes with larger aggregates) promise to revolutionise construction [65, 66]. By overcoming current barriers and fully leveraging technological innovation, robotics is set to become a foundational pillar of the sector's digital transformation [68].

3.2.3 Digital Information Solutions

Digital Information solutions are technological tools and systems that support the efficient generation, management, and exchange of digital data throughout all phases of a construction project lifecycle. Notably, BIM-based approaches, when combined with emerging technologies such as DTs, XR, IoT, AI, and Deep Learning, offer significant advantages in terms of data integration, visualisation, simulation, and real-time monitoring. While Digital Information solutions aim to facilitate a seamless transition across the design, construction, and operational management phases, several barriers limit their effectiveness, including industry fragmentation, the absence of standardised data protocols, and insufficient client demand. To overcome these challenges, strategies such as adopting interoperable standards, implementing structured workflows, and actively involving clients in defining requirements and promoting stakeholder coordination can help realise the full benefits of these technologies. This section explores how such synergies enhance safety, decision-making, and effective collaboration throughout the construction process.

3.2.3.1 Information Modelling solutions

Information Modelling solutions primarily rely on BIM, which acts as the core methodology and digital backbone for organising, structuring, and managing building data throughout its lifecycle. Digitalisation, especially via BIM, has strong potential to transform project organisation and financing [69]. According to Wang et al. [70], seven key factors influence professionals' willingness to collaborate on BIM-enabled projects: professional knowledge and skills, training, investment, BIM and collaboration tools, BIM ownership, standards, and regulations. Among these, professional knowledge is one of the most critical factors [70]. As projects grow in complexity, particularly in high-rise, healthcare, and educational infrastructure, there is an urgent need for advanced digital platforms that extend beyond traditional planning and monitoring [39]. An example of a digital platform is CDE, a central platform that stores, manages, and shares project information among all project stakeholders, ensuring trust, transparency, and traceability in BIM workflows. In general, a digital platform enables users to track the development, maintenance, and decommissioning of the built asset, thereby supporting long-term documentation and learning [71].

The need for collaborative environments for information sharing is becoming increasingly pressing, especially in the public sector, where the widespread adoption of BIM methodologies and the reform of public procurement regulations across Europe are driving demand for digital models in public works projects [38]. Furthermore, recent studies underscore the importance of integrated BIM-based platforms for the intelligent management of high-rise building projects. These platforms offer dynamic BIM model generation, real-time progress monitoring, and quality tracking, significantly improving construction efficiency and reducing scheduling errors. In one case, a BIM-integrated platform achieved 91.89% data-processing efficiency, demonstrating its practical applicability [39].

Traditionally, BIM is used mainly during the design phase alongside 2D drawings. Early-stage BIM modelling tools improve planning, hazard detection, and team communication [72]. Disney et al. introduce "Total BIM," an innovative approach that treats BIM as the sole source of information throughout all project phases [73], eliminating 2D paper drawings On-site. BIM becomes the contractual and legally binding construction document, thereby conferring a higher legal status than traditional drawings. Utilising high-quality, production-oriented, cloud-based BIM ensures that all stakeholders have access to up-to-date information. The use of user-friendly mobile BIM software enables site workers to generate construction information directly from BIM, thereby facilitating better On-site decision-making. The Total BIM case study emphasises a holistic approach, integrating disparate BIM applications into a cohesive strategy. This integration helps reduce errors, improve productivity, and ultimately deliver projects more efficiently [37, 73].

BIM is essential in construction site management, providing a digital representation of a project's physical and functional characteristics. In recent years, the adoption of innovative technologies on construction sites has expanded considerably, driven by their value proposition in enhancing On-site efficiency, integrating project teams, and enabling effective information sharing [74]. These technologies can support the principles of lean construction by improving visualisation, value management, and workflows, and by reducing On-site waste [75]. BIM enables virtual prototyping and simulation of construction processes, aiding planning and optimisation of site activities [76]. Mature BIM management experience can enhance On-site process control and ensure both progress monitoring and safety during

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the construction phase [77, 78]. By visualising construction elements in a digital environment before physical execution, BIM enables early detection and resolution of potential issues, an essential element of effective risk management [79]. When integrated with other technologies, BIM can support geometric verification of built structures [80] or monitor work progress [81] by comparing cloud point or imagery with the digital model. The objective is to reconstruct "as-built" elements and compare them with the "as-planned" information in the BIM environment [82].

Despite its advantages, the application of BIM in construction site management depends on accurate On-site data. The lack of technology for creating digital models that accurately reflect On-site conditions can delay BIM implementation [83]. BIM also advances sustainable construction by integrating technologies and effective construction processes, delivering substantial benefits. Murti and Muslim [84] identify building digitalisation, improvements over traditional 2D CAD methods, and the integration of various construction tools as elements of BIM that positively influence sustainable construction. For instance, BIM provides detailed insights into material quantities, optimising their use, and managing construction waste, thereby reducing both costs and environmental impact [80].

Table 6. Summary of the analysis of Information Modelling solutions, reporting improvement levels, application areas, and the main benefits and challenges identified in the literature.

	Tot. Articles	**Identified articles**
On-site automation solutions	63	[19–21, 27–31, 33, 35–42, 44, 52, 57–59, 65, 69–108]
Topic	**Typology**	**Reference**
Improvement level	• Enabling improvement	[72, 74, 83]
	• Qualitative improvement	[39, 79, 80, 89]
	• Quantitative improvement	[77, 88]
	• Safety improvement	[72, 79, 81]
Application areas	• Project planning and design	[36, 76, 86]
	• Project management	[36, 71, 73, 85]
	• Health and safety	[38, 79, 81, 87]
	• On-site operation, logistics and supply chain	[36, 39, 73, 79, 83]
	• Construction methods	[72, 73, 78, 84]
	• Structural health assessment	[72, 81, 84]
Benefits	• Improves communication and collaboration	[38, 70, 84, 88, 95]
	• Increases productivity and efficiency in construction processes and projects	[40]
	• Reduces project costs, time, and errors	[71, 83, 88, 95]
	• Enhances project quality	[70, 71]
	• Helps manage different types of information	[69]
Challenges	• High initial investment (IT infrastructure and qualified personnel)	[88]
	• Sometimes a lack of supporting legislation	[85, 95]
	• Lack of standards and difficulties with software interoperability	[70]
	• Resistance from workers to changing traditional work methods	[79, 85]

With advances in digitalisation, the DT concept has become increasingly popular. According to Salem and Dragonil [85], their implementation in construction needs a three-stage model, characterised respectively by BIM, which is widely used for lifecycle management, current monitoring and actuation DTs, focusing on smart homes and cities, and lastly an envisioned model that automates decision-making on construction sites, minimising human intervention [85]. While BIM is effective for representing physical facilities, it falls short of depicting construction operations. This limitation necessitates the integration of simulation modelling to create a DT [86]. Implementing BIM models with IoT devices and AI algorithms enables DT [36, 69], which supports predictive maintenance, energy optimisation, and automation through real-time data collection and simulation, as well as precise progress tracking, scenario simulation, and proactive responses to unforeseen events [36, 77]. By fully embracing BIM, the project not only improved construction processes but also provided the client with a DT for facility management, showcasing the long-term benefits of a comprehensive strategy [37, 73].

In summary, BIM has evolved from a design tool to a comprehensive project management solution that enhances

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collaboration, efficiency, and accuracy in construction projects [37, 73]. It is promoted as a means to transform the construction industry by enhancing productivity, safety, schedule adherence, and cost efficiency [87]. Despite the recognised benefits, the adoption remains limited in many countries. Factors contributing to low uptake include lack of digital skills, resistance to change, inadequate infrastructure [88], lack of demand from clients and perception of BIM implementation as additional work [84], lack of guidelines and frameworks for implementation, higher initial costs compared to traditional practices, absence of standardised data integration and management protocols, difficulty in adopting technological advancements [86], interoperability and integration of various BIM tools as critical to successful implementation [72]. In conclusion, BIM is rapidly establishing itself as a fundamental methodology in the construction sector, with its tools and practices seeing widespread adoption. Nonetheless, the persistent challenges to its full implementation present valuable opportunities to develop complementary support tools [89].

3.2.3.2 Extended Reality solutions

In recent years, XR solutions have gained attention within the AEC sector [41]. Alongside terms such as '3D reconstruction', 'IoT technologies', and 'Smart Construction Site', XR has become a key topic in research works, particularly over the past decade [41]. The AR/VR market has reached multi-billion-dollar valuations, with an annual growth rate of 40.29% between 2020 and 2023 [44]. Beyond simply adopting advanced tools like XR, a smart construction site emphasises leveraging them to enhance productivity and improve management performance in construction engineering. The integration of smart tools into contemporary construction practices is essential for improving safety, optimising processes, and boosting overall project efficiency [41].

VR, AR, and MR are distinct yet interrelated technologies within the broader XR framework. VR is used in construction for education and training purposes, offering an interactive, computer-generated environment that immerses users in real-time simulations of construction activities [106]. In contrast, AR superimposes digital information onto the physical environment, enhancing users' perception while maintaining their connection to the real world. This makes AR particularly effective for conveying project-related information to construction workers and stakeholders, rather than relying on 2D drawings [41, 98]. MR bridges the gap between VR and AR by enabling real-time interaction between digital and physical elements; virtual objects are not only anchored to the real environment but also respond to it dynamically.

Each technology offers varying degrees of user interaction and integration with virtual content [42]. XR applications are integral to the digitisation process in the sector, commonly referred to as Construction 4.0 [107], marked by increasing connectivity and integration. BIM remains a foundational technology [98]. A key challenge in BIM implementation is the interoperability of files generated by different authoring software. Currently, the standard exchange format within the openBIM framework is the Industry Foundation Classes (IFC), a standardised data schema based on the EXPRESS modelling language and regulated by the STEP standard (ISO 10303-11). IFC data can be converted into visualisation-friendly formats such as JSON or OBJ, thereby enabling integration with XR applications and game engines, including Unity [98]. Through digital platforms, BIM data can be utilised in serious games, which offer realistic, interactive training environments for both practical field skills and theoretical knowledge. These simulations allow users to engage with virtual construction scenarios, enhancing skill development in a controlled setting [96, 98, 106]. Complementary to BIM-based workflows, Reality Capture (RC) technologies enable the generation of accurate as-built 3D point cloud models that can be directly integrated into the same XR platforms, bridging the gap between design intent and the actual built environment [94].

Among the analysed literature, XR is widely studied for construction safety, with a primary application in worker training, predominantly through VR and serious game engines. These tools enhance safety knowledge, hazard recognition, and situational awareness by simulating real-world construction site scenarios. Studies show that VR-based training is more effective than traditional classroom methods and more engaging for trainees [42]. Moreover, training environments enable data collection on user behaviour and performance, offering insights into how these are influenced by factors such as task complexity, workload, and time pressure. VR-based immersive safety education enables behavioural trials in virtual environments, allowing individuals to handle safety hazards that would be too costly or risky on real construction sites [43]. Additionally, researchers have integrated AR and MR into active construction sites to enhance hazard awareness, using real-time alerts and visual prompts to help workers identify potential risks [41].

Table 7. Summary of the analysis of Extended Reality solutions, reporting improvement levels, application areas, and the main benefits and challenges identified in the literature.

	Tot. Articles	Identified articles
On-site automation solutions	10	[41–44, 94, 96, 98, 100, 106, 107]

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Topic	Typology	Reference
Improvement level	• Enabling improvement • Qualitative improvement • Quantitative improvement • Safety improvement	[41, 43, 90, 96, 98, 106] [41, 44, 96, 98, 100] [42, 94] [41–44, 86, 9[illegible]]
Application areas	• Project planning and design • Project management • Health and safety • On-site operation, logistics and supply chain • Construction methods • Structural health assessment	[41, 44, 9[illegible], 96, 98, 106] [41, 44, 94, 96, [illegible]6, 107] [41–44, 96, 100] [4[illegible], [illegible]6, 106, 1[illegible]7] [41, 4[illegible], 44, 96, 100] [41]
Benefits	• Enables immersive, risk-free safety training in realistic virtual environments, enhancing engagement and retention. • Data on user accuracy and reaction time can be automatically collected for performance analysis. • Combined with BIM, it enhances spatial understanding, collaboration, and error detection, while mitigating project-related contractual issues between stakeholders. • Provide hands-free, context-aware instructions and overlays, reducing reliance on paper drawings and enhancing task accuracy and safety. • Facilitates intuitive comparison between as-built and as-planned states by superimposing BIM data onto real site conditions	[41, 43, 44, 96, 106] [43] [41, 42, 44, 94, 96, 98] [42, 43, 98, 100] [41, 44, 98]
Challenges	• XR hardware faces challenges such as occlusion, environmental instability, and difficult user interactions, limiting its practicality on-site. • Lack of realism in training or educational application of XR (idealised environments, limited integration of real-time site data). • Developing complex scenarios is a highly time-consuming and resource-intensive task. • Limited or no predictive capabilities for hazard detection • Most XR applications remain at prototype stages, with little evidence of scalability (high costs) or long-term deployment in real-world construction environments.	[41–44, 94, 96, 98, 100] [41, 42, 106] [41, 42, 106] [41, 44] [41, 42, 100, 106]

AR can be employed to enhance accuracy, speed, and safety in construction tasks. For instance, Fazel and Adel present an integrated system that combines AR with a real-time feedback mechanism [100]. This system monitors key safety parameters (e.g., orientation error, position error, and hand placement). It automatically interrupts power to the tool if the operator is not working under safe conditions. XR technologies, especially AR and MR, when integrated with deep learning, support enhanced safety and compliance checks on construction sites by enabling real-time monitoring, automated hazard detection, and immersive training simulations. These systems improve hazard awareness, streamline compliance verification, and provide data-driven insights to support proactive safety management [41]. On-site AR supports the construction inspection. When integrating BIM and sensor data, XR tools enable advanced analytical capabilities that not only generate safety insights and compliance reports but also help verify the spatial accuracy of built elements and equipment placement against the design model. This integration enhances situational awareness and facilitates more informed decision-making throughout the construction process [41, 42].

Despite advancements, XR devices face significant barriers to adoption in construction safety training. Common

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issues include high costs, limited fields of view, motion sickness, and lack of realistic feedback (which reduces training effectiveness). Technical constraints, such as latency, limited processing power, and sensitivity to environmental conditions (e.g., lighting), further restrict performance. Additionally, interoperability issues with existing systems, data privacy concerns, and the need for user training limit scalability (particularly for smaller firms). Marker-based tracking and reliance on costly hardware are also impractical in dynamic, real-world settings. Accurate tracking of AR models on construction sites is essential for effective inspections; however, most AR tracking systems still struggle to maintain precision over longer distances, which can pose serious issues on large-scale construction sites [41, 98, 100, 106].

VR is widely used in construction safety training, but replicating the multi-hazard nature of real construction sites remains challenging. Creating realistic scenarios is resource-intensive, requiring technical expertise and investment. When using the project BIM model as the basis for scenario development, its LOD is insufficient, and detailed modelling is required [106]. VR applications also require high data throughput, which can burden the infrastructure, whereas mobile-based systems often sacrifice immersion quality. Many training modules are hazard-specific and lack generalisability. Limited interactivity and low digital literacy among workers further diminish the effectiveness of training [42, 106]. Future development should prioritise expanding visual fields, reducing discomfort, lowering costs, and integrating haptic feedback to simulate real-world interactions and enhance learning outcomes [42].

4. Discussion

This section interprets the results with a focus on the integration and maturity of digital solutions. In particular, it examines the existing literature considering: (i) interactions among the three main categories (Data Acquisition solutions, Digital Fabrication and Automation solutions, and Digital Information solutions) and (ii) differences in maturity, applicability, and integration across the six identified digital solutions.

Building on the research landscape's fragmentation, the analysis provides further insights into intersections and distribution patterns of the six digital solutions in the literature, with particular attention to their combined investigation. Venn diagrams (Fig. 6), constructed from a subset of the 86 articles excluding review papers, were used to intuitively visualise these relationships, offering two levels of analysis: (i) interactions among the three main categories (Fig. 6a), and (ii) co-occurrence patterns among the six digital solutions in a granular way (Fig 6b-d). This approach highlights emerging integration pathways among the studies and supports the discussion of where integration remains limited.

The distribution of publications reported in Figure 6a, showcasing Data Acquisition (grey), Digital Fabrication and Automation solutions (purple), and Digital Information (light blue), reveals a clear imbalance. Digital Information solutions dominate the reviewed literature set with 25 publications [36–39, 69, 71–77, 83, 84, 88, 95–100, 102, 103, 105, 106] whereas 5 publications address only Data Acquisition solutions [22, 23, 25, 27, 109], and 11 studies focus only on Digital Fabrication and Automation [53–5[illegible], [illegible]–63, 67, 68]. Although some studies explore combinations of categories, only a limited number integrate two of them or all three: 11 publications cover both Data Acquisition and Digital Information [19–21, 27, 80, 82, [illegible]5, [illegible]–93, [illegible]10] while 8 cover Digital Information and Digital Fabrication and Automation [30, 35, 40, 52, 59, 64, 65, [illegible]]. Only 3 publications address the intersection of all three main categories [29, 57, 58]. Notably, no studies explicitly combine Data Acquisition and Digital Fabrication solutions. This gap suggests the absence of works linking data capture to the production and assembly chain workflows. Such approaches, already established in manufacturing contexts, are still underdeveloped in construction.

A more detailed analysis of co-occurrence patterns (Fig 6b-d) among the six digital solutions offers further insights, highlighting where integrated approaches are emerging and where digital solutions remain isolated.

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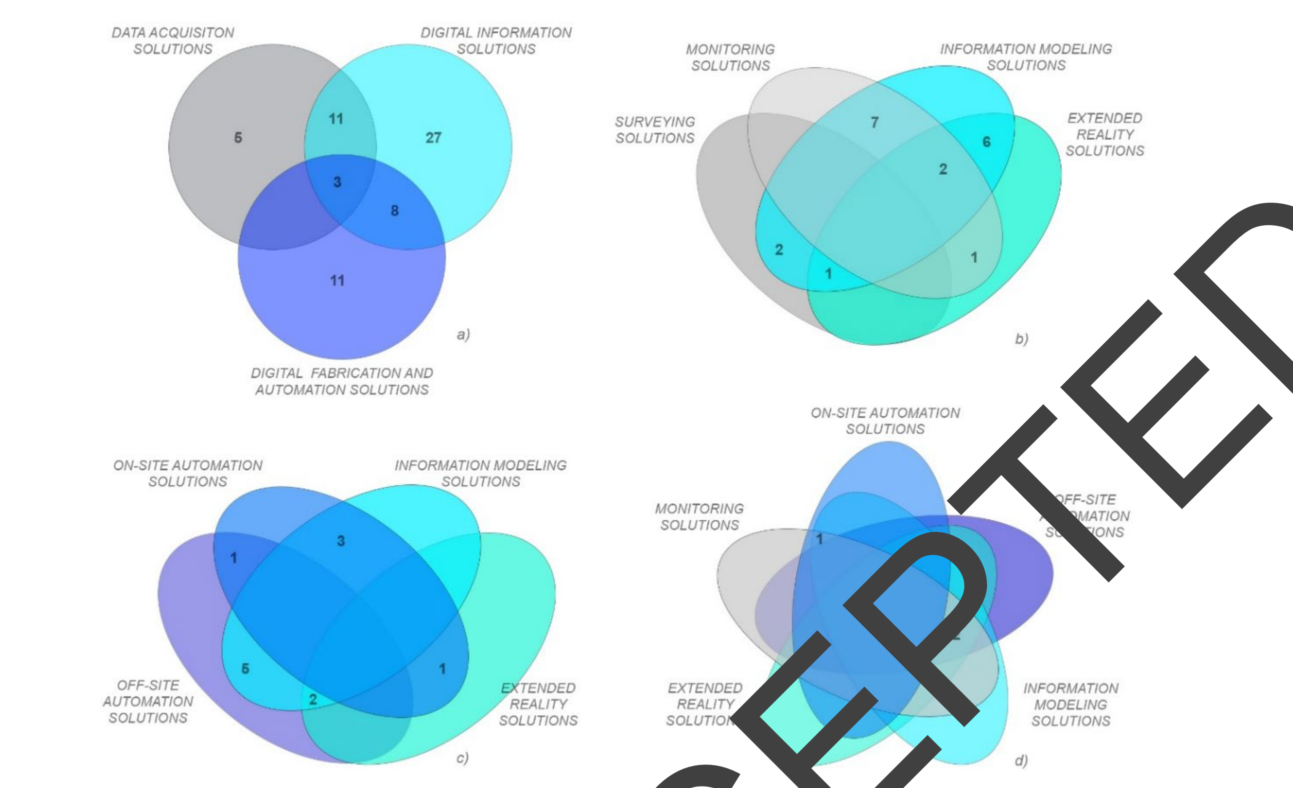

Figure 6 – Venn diagrams illustrating overlap across digital solution categories and their associated digital solutions: (a) interactions among the three main categories; (b–d) intersections among the six digital solutions identified within these categories, with colours consistently reused to indicate related domains.

Figure 6b) explores the relationships between Surveying solutions (dark grey), Monitoring solutions (light grey), Information Modelling solutions (light blue), and Extended reality solutions (aqua green). The most significant overlap is observed between Monitoring solutions and Information Modelling solutions, with 7 publications [27, 80, 82, 85, 91–93]. These studies predominantly integrate reality-capture technologies (e.g., UAS-based photogrammetry and terrestrial laser scanning), CV and deep learning techniques, robotic systems, and cloud-based data-acquisition platforms with BIM environments, DT, and semantic data models. This convergence enables applications such as automated safety inspections, geometric verification, progress tracking, and construction site analytics by continuously transforming raw site data into structured digital representations.

There are also intersections between Surveying solutions and Information modelling solutions [20, 21] and between Monitoring solutions and Extended reality solutions [110]. In the former, common technologies include UAS-based photogrammetry, reality capture, deep learning–based CV, and BIM-enabled digital twins, supporting the integration of surveyed data into structured information models. In the latter, data acquired through drones, sensors, and CV are coupled with DT and XR environments, enabling immersive visualisation and interaction with the construction site.

The intersection area among all four digital solutions is empty, indicating that most implementations rely on partial integration. Differences in maturity and integration potential are evident within Data Acquisition solutions: both Monitoring and Surveying solutions are linked to Information Modelling and XR, suggesting emerging pathways. Monitoring solutions exhibit greater integration with other digital technologies, reflecting maturity and broader application scopes. In contrast, Surveying solutions remain rooted in a specialised and historically niche field, such as topography, making them less transversal and less integrable with other digital tools. Despite their relevance in defining and managing standardised data in digital processes, few studies address these aspects, highlighting a lack of shared standards and consistent methodologies in the literature.

Certainly, in Figure 6b), the central role of Information Modelling is highlighted, which frequently acts as a connecting element across different digital solutions, as confirmed also in Figure 6c). The latter showcases the relationship between Information Modelling solutions (light blue), Extended reality solutions (aqua green), On-site automation solutions (blue), and Off-site automation solutions (purple). 3 studies show the link between On-site automation solutions and Information Modelling solutions [29, 30, 65], regarding BIM-driven workflows supporting autonomous excavation, robotic construction, and large-scale On-site 3D concrete printing, underscoring the importance of structured information for automation and data continuity. 5 publications connect Off-site automation

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solutions and Information Modelling solutions [35, 40, 52, 59, 78], showing how BIM with GIS and algorithm-aided modelling supports prefabrication, modular construction, and optimised manufacturing, delivery, and assembly.

Only 1 publication has been identified among On-site automation, Off-site automation, and Information modelling solutions [35], focusing on BIM-based management and data-transfer frameworks for both Off-site fabrication and On-site construction processes.

Another intersection concerns On-site automation and XR solutions [64], in which AR systems use real-time site data to visualise and retrieve information from moving objects. Only one overlapping area in the diagram involves more than two digital solutions, corresponding to 2 publications that simultaneously address XR, Off-site automation, and Information Modelling solutions. The graph suggests limited technological convergence between Digital Fabrication and Automation solutions and Digital Information solutions, indicating a broader lack of integration across design, fabrication, and construction. Strengthening this integration is essential to enabling scalable, efficient automated systems in both On-site and Off-site environments.

The combined analysis shown in Figure 6d) further highlights the scarcity of studies addressing multiple digital solutions simultaneously among the six identified. Intersections include 2 publications on Off-site automation, Information Modelling, Monitoring, and XR solutions [57, 58], addressing digital construction management platforms that integrate BIM-based information models with IoT-enabled monitoring devices, interoperable data standards, and XR interfaces, supporting coordinated Off-site production, On-site data acquisition, and immersive environments. Moreover, 1 publication is identified at the intersection of Monitoring, On-site automation, and Information modelling solutions [29], regarding operational technology systems, including IoT-enabled sensors and automated equipment, as well as BIM-based information environments for managing and securing real-time construction site data.

Overall, the first level of the analysis highlights the fragmented nature of the AEC sector and the interoperability challenge among digital technologies. Information Modelling is one of the most widely adopted digital solutions in the built environment and is closely linked to Monitoring solutions, often serving as the foundational layer for real-time data integration. On-site automation solutions are deeply intertwined with Monitoring, Information Modelling, and XR solutions, but rarely linked to Surveying solutions. The integration with BIM platforms provides robotic systems with geometric and semantic information about built elements, enabling optimised trajectory planning and Off-site operations, improving precision beyond manual methods. Similarly, XR solutions are embedded directly within robotic workflows, allowing digital designs, tolerances, and fabrication instructions to be overlaid onto physical components. For example, the Augmented Drawn Construction Symbols (ADCS) method converts hand-drawn markings into digital instructions for robots, rendering interaction intuitive for non-specialist operators and facilitating real-time adaptation to construction tolerances.

The relatively low numbers in the overlapping areas appear to reflect the fragmented nature of the AEC sector and the interoperability challenge, as observed in the thematic dispersion of keyword co-occurrences in the Results section. While these analyses provide insight into how digital solutions are combined within the literature, they do not capture differences in technological maturity, breadth of application, or interoperability potential across them.

To address this gap, this study introduces a KPI-based framework that enables a multi-dimensional evaluation of digital solutions. This approach extends prior SLRs by providing a comparative and interpretive tool contributing to further research and applications. The framework is based on three indicators: Technology Readiness Level (TRL), Application Areas Level (AAL), and Integrability Level (IL), synthesised into radar charts (Fig. 7) that serve as a multi-dimensional comparative assessment tool.

TRL measures technology maturity on a scale from 1 to 9 [111]. The AAL assesses the feasibility of applying a digital solution to a specific area [90]. These are: 1) Project planning and design, 2) Project management, 3) Health and safety, 4) On-site operation and logistics and supply chain, 5) Construction methods, 6) Structural health assessment. The values of AAL range from 1 (application of a digital solution to a single area) to 6 (application across all areas) and were assigned based on Tables 3, 4, 5, 6, 7, 8 reported in the Results section. The last indicator, IL, describes the ability to integrate two or more digital solutions. The values correspond to the intersections of Veen sets, ranging from 1 to 6, since six digital solutions were identified.

The KPI-based radar charts reveal distinct profiles across the digital solutions. Among all radars, Digital Information Solutions, including Information Modelling solutions and Extended Reality, show strong relevance across all AALs. This result aligns with their primary purpose of enhancing quality in the AEC sector and facilitating information exchange across project phases and among stakeholders.

The Information Modelling solution also displays the highest TRL value, based exclusively on the studies included in the SLR; accordingly, Extended Reality and Monitoring Solutions still exhibit significant TRL gaps, particularly in hardware and other supporting aspects. This indicates that, although XR has many recognised application areas, its integration with other digital solutions on construction sites remains limited. According to the selected studies, these challenges are mainly due to high device costs and technical limitations that affect On-site use. On the hardware side,

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short battery life, overheating, exposure to weather conditions, and the difficulty of integrating head-mounted displays with safety helmets all reflect an ongoing need for technological adaptation to enable practical field deployment.

The radar chart analysis of the Surveying solutions reveals a low IL, indicating a limited tendency to employ these digital solutions alongside other tools, despite their favourable AAL rating of 5 out of 6. Consequently, surveying solutions appear compatible with and integrable into other digital technologies currently used in the construction sector. However, there is a lack of research.

Fragmentation across various solutions is evident, particularly in the manufacturing phase (Digital Fabrication and Automation). Off-site automation solutions offer the lowest IL, though this may be offset by a marked verticalisation of technology. On-site automation solutions in the construction sector have reached TRL 7, as numerous prototypes have been successfully demonstrated in realistic operational environments and through experiments [32, 62, 63–65]; moreover, they show strong integrability and versatility, being used in multi-instrument assemblies and On-site manufacturing [64].

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Figure 7 – KPI-based radar charts for the assessment of each of the six digital solutions identified.

5. Conclusion

The paper proposes a systematic literature review (SLR) to examine the evolution of digital solution adoption in building construction over the past decade. Through an analysis of 86 publications selected from the Scopus and Web of Science databases, the study sought to identify challenges and opportunities in data integration across various digital solutions and to provide an overview of their technology maturity, application areas, and interoperability.

The bibliometric analysis highlights a growing interest in digital technologies, particularly since 2020. Although the interest is global, the research landscape remains fragmented, with studies scattered across many journals and covering a wide range of topics. Building on the keywords' co-occurrence analysis, three main categories of digital solutions have been identified: i) Data Acquisition solutions, ii) Digital Fabrication and Automation solutions, and iii) Digital Information solutions. Within them, the literature analysis identified six main digital technologies, which were analysed with respect to their characteristics and interrelations.

The review of the 86 articles highlights ongoing challenges related to interoperability and inconsistent adoption of digital technologies. In the discussion section, the analysis is further developed through a visual interpretation of the results, examining how publications are distributed across the three main categories. Diagrams were created to identify how many studies address more than one digital technology and which ones do; most studies focus on one category, while only a small core of publications investigates the intersection of the three main categories.

A key contribution of this work lies in a structured analysis of the six digital solutions, combined with the development of an interpretative KPI-based framework that enables a multi-value comparative analysis, visualised through radar charts reporting Technology Readiness Level (TRL), Application Areas Level (AAL), and Integrability Level (IL), providing a useful tool for both researchers and practitioners.

The findings show that Digital information solutions, particularly Information modelling solutions and Extended Reality, demonstrate broad coverage of AALs, reflecting their strong potential to enhance information management and process quality. In terms of technological maturity, Information Modelling solutions appear ready for deployment within the sector, whereas Extended Reality and Monitoring solutions still exhibit notable gaps in readiness. The IL analysis revealed persistent fragmentation, especially for prefabrication-related solutions. Data acquisition and Digital Fabrication and Automation solutions are considered only partially integrable. Extended Reality is often characterised as poorly integrable, although research highlights new interaction modalities.

Despite documented benefits across the various digital solutions (i.e. increased productivity, efficiency, safety, and quality), widespread adoption is hindered by factors such as high technical complexity, elevated costs, lack of qualified personnel, resistance to change, challenges in adapting to changing site conditions, and, above all, a lack of standards and difficulties in interoperability among software and systems. The fragmented processes in the AEC sector and the vast heterogeneity of the data pose a critical challenge to realising the full potential of digital transformation.

The field's emerging nature suggests areas for future research. Opportunities lie in integrating BIM with emerging technologies such as IoT, AI, XR, and DTs, which is considered crucial for improving data management, visualisation, simulation, and real-time monitoring. Concepts such as "Total BIM," which promotes the BIM model as the single source of information throughout the project lifecycle, represent a step forward toward greater integration and reliability. It is necessary to develop interoperability and integration across categories of digital solutions, establish shared standards, and address adoption barriers at the organisational, technical, and regulatory levels. Further efforts should also focus on real-world validation, scalability, and the adaptation of technologies to dynamic site conditions to facilitate the effective implementation of digital solutions.

Overall, despite significant progress, the AEC sector must address interoperability challenges to fully realise the potential of digital solutions to enhance construction processes and promote efficiency, safety, and sustainability.

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7. Authors' Contributions

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All authors reviewed and approved the final version of the manuscript.

8. References

1. Koscheyev V, Rapgof V, Vinogradova V (2019) Digital transformation of construction organizations. IOP Conf Ser: Mater Sci Eng 497:1–7. https://doi.org/10.1088/1757-899X/497/1/012010
2. Associazione Infrastrutture Sostenibili (AIS) (2022) Il cantiere sostenibile
3. Build Up (2019) Digitalisation in the construction industry. In: Build Up - The European portal for energy efficiency in buildings. https://www.buildup.eu/en/news/overview-digitalisation-construction-industry. Accessed 8 Feb 2025
4. Pauwels P, Zhang S, Lee YC (2017) Semantic web technologies in AEC industry: A literature overview. Automation in Construction 73:145–165. https://doi.org/10.1016/j.autcon.2016.10.003
5. Pauwels P, De Meyer R, Van Campenhout J (2011) Interoperability for the Design and Construction Industry through Semantic Web Technology. In: Declerck T, Granitzer M, Grzegorzek M, et al (eds) Semantic Multimedia. Springer Berlin Heidelberg, Berlin, Heidelberg, pp 1[illegible]–158
6. Mancuso I, Petruzzelli AM, Panniello U (2024) Industry 4.0 for AEC Sector: Impacts on Productivity and Sustainability. In: Barberio M, Colella M, Figliola A, Battisti A (eds) Architecture and Design for Industry 4.0: Theory and Practice. Springer International Publishing, Cham, pp [illegible]–50
7. Kieran S, Timberlake J (2004) Refabricating ARCHITECTURE: How Manufacturing Methodologies are Poised to Transform Building Construction. McGraw Hill Professional
8. Pearson YE, Alexander QG, Cropps TA, Walker Thornton TA (2025) Opportunities for Advancing ESG Principles through Academic–Workforce Collaborations. J Manage Eng 41:05025003-1-05025003–13. https://doi.org/10.1061/JMENEA.MEENG-6656
9. How the AEC sector can improve ESG performance. In: CreativeITC. https://www.creative-itc.com/how-the-aec-sector-can-improve-esg-performance/. Accessed 8 Feb 2025
10. Ambegaonkar R Beyond Green Building: ESG Compliance as a Competitive Advantage in the AEC Sector. In: ny-engineers. https://www.ny-engineers.com/blog/beyond-green-building-esg-compliance-as-a-competitive-advantage-in-the-aec-sector. Accessed 9 Feb 2025
11. (2023) What role does ESG play in the built environment? In: Buro Happold. https://www.burohappold.com/insights/what-role-does-esg-play-in-the-built-environment/. Accessed 9 Feb 2025
12. Barbosa F, Woetzel J, Mischke J, et al (2017) Reinventing construction: a route to higher productivity. Mckinsey Global Institute
13. How the AEC Industry is Embracing Digital Transformation. In: Mirror review. https://www.mirrorreview.com/aec-industry/. Accessed 9 Feb 2025
14. Geospatial World (2022) Mega Trends Driving Digital Transformation in Europe's AEC Industry
15. Zhao Y, Han Z, Wang L (2024) Digitization path to improve ESG performance: A study on organizational perspective. PLoS ONE 19:1–20. https://doi.org/10.1371/journal.pone.0313686
16. Page MJ, McKenzie JE, Bossuyt PM, et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Systematic Reviews 10:1–11. https://doi.org/10.1186/s13643-021-01626-4
17. Mukherjee D, Lim WM, Kumar S, Donthu N (2022) Guidelines for advancing theory and practice through bibliometric research. Journal of Business Research 148:101–115. https://doi.org/10.1016/j.jbusres.2022.04.042
18. Öztürk [illegible], Kocaman R, Kanbach DK (2024) How to design bibliometric research: an overview and a framework proposal. Review of Managerial Science 18:3333–3361. https://doi.org/10.1007/s11846-024-00738-0
19. [illegible] Salem T, Dragomir M, Chatelet E (2024) Strategic Integration of Drone Technology and Digital Twins for Optimal Construction Project Management. Applied Sciences 14:1–15. https://doi.org/10.3390/app14114787
20. Ekanayake B, Wong JKW, Fini AAF, et al (2024) Deep learning-based computer vision in project management: Automating indoor construction progress monitoring. Project Leadership and Society 5:1–13. https://doi.org/10.1016/j.plas.2024.100149
21. Torres J, San-Mateos R, Lasarte N, et al (2024) Building Digital Twins to Overcome Digitalization Barriers for Automating Construction Site Management. Buildings 14:1–32. https://doi.org/10.3390/buildings14072238
22. Qureshi AH, Alaloul WS, Hussain SJ, et al (2023) Evaluation of Photogrammetry Tools following Progress Detection of Rebar towards Sustainable Construction Processes. Sustainability 15:1–35. https://doi.org/10.3390/su15010021

https://doi.org/10.36253/tema-16926

23. Cho J-W, Lee J-K, Park J (2021) Large-Scale Earthwork Progress Digitalization Practices Using Series of 3D Models Generated from UAS Images. Drones 5:1–16. https://doi.org/10.3390/drones5040147
24. Arshad S, Akinade O, Bello S, Bilal M (2023) Computer vision and IoT research landscape for health and safety management on construction sites. Journal of Building Engineering 76:1–12. https://doi.org/10.1016/j.jobe.2023.107049
25. Tabatabaee S, Mohandes SR, Ahmed RR, et al (2022) Investigating the Barriers to Applying the Internet-of-Things-Based Technologies to Construction Site Safety Management. Int J Environ Res Public Health 19:1–15. https://doi.org/10.3390/ijerph19020868
26. Maali O, Ko C-H, Nguyen PHD (2024) Applications of existing and emerging construction safety technologies. Automation in Construction 158:1–16. https://doi.org/10.1016/j.autcon.2023.105231
27. Rey RO, De Melo RRS, Costa DB (2021) Design and implementation of a computerized safety inspection system for construction sites using UAS and digital checklists – Smart Inspecs. Safety Science 143:1–[illegible]. https://doi.org/10.1016/j.ssci.2021.105430
28. Ibrahim FS, Esa M, A. Rahman R (2021) The Adoption of IOT in the Malaysian Construction Industry: Towards Construction 4.0. IJSCET 12:56–67. https://doi.org/10.30880/ijscet.2021.12.01.006
29. Prieto SA, Giakoumidis N, García De Soto B (2024) Multiagent robotic systems and exploration algorithms: Applications for data collection in construction sites. Journal of Field Robotics 41:1187–1203. https://doi.org/10.1002/rob.22316
30. Hiltunen M, Heikkilä R, Niskanen I, Immonen M (2023) Open InfraBIM for remote and autonomous excavation. Automation in Construction 156:1–10. https://doi.org/10.1016/j.autcon.2023.1051[illegible]
31. Karimi S, Iordanova I (2021) Integration of BIM and GIS for Construction Automation, a Systematic Literature Review (SLR) Combining Bibliometric and Qualitative Analysis. Arch Comput Methods Eng 28:4573–4594. https://doi.org/10.1007/s11831-021-09545-2
32. Classen M, Ungermann J, Sharma R (2020) Additive Manufacturing of Reinforced Concrete—Development of a 3D Printing Technology for Cementitious Composites with Metallic Reinforcement. Applied Sciences 10:1–13. https://doi.org/10.3390/app10113791
33. Sonkor MS, García De Soto B (2021) Operational Technology on Construction Sites: A Review from the Cybersecurity Perspective. Journal of Construction Engineering and Management 147:04021172-1-04021172–22. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002193
34. Smith RE (2010) Prefab architecture: A guide to modular design and construction. John Wiley & Sons
35. Lei Z, Sadiq Altaf M, Cheng Z, et al (20[illegible]) Measurement of Information Loss and Transfer Impacts of Technology Systems in Offsite Construction Processes. Journal of Construction Engineering and Management 149:05023011. https://doi.org/10.1061/J[illegible]EMD4.COE[illegible]G-13637
36. Piras G, Muzi F, Tiburcio VA (2024) Digital Management Methodology for Building Production Optimization through Digital Twin and Artificial Intelligence Integration. Buildings 14:1–23. https://doi.org/10.3390/buildings[illegible]4072[illegible]
37. Disney O, Roupé M, Johansson M, et al (2023) Total BIM on the construction site: a dynamic single source of information. Journal of Information Technology in Construction 28:519–538. https://doi.org/10.[illegible]680/j.itcon.202[illegible]027
38. Lo Turco M, [illegible]ncino MM (2016) Collaborative environments for knowledge sharing: First building information modeling applications for public works. DISEGNAREcon 9:7.1-7.10
39. Deng R, Li C (2022) Digital Intelligent Management Platform for High-Rise Building Construction Based on BIM Technology. International Journal of Advanced Computer Science and Applications 13:1057–1067. http[illegible]dx.doi.org/10.14569/IJACSA.2022.01312121
40. Chid[illegible]m S (2[illegible]19) Application of building information modelling for reinforcement waste minimisation. Proceedings of the Institution of Civil Engineers - Waste and Resource Management 172:3–13. https://doi.org/[illegible].1680/jwarm.17.00027
41. Lee [illegible], Rashidi A, Talei A, et al (2022) Integration of deep learning and extended reality technologies in construction engineering and management: a mixed review method. Construction Innovation: Information Process Management 22:671–701. https://doi.org/10.1108/CI-04-2022-0075
42. [illegible] M, Shafiq MT, Jassmi HA (2021) Improving construction safety with virtual-design construction technologies – a review. ITcon 26:319–340. https://doi.org/10.36680/j.itcon.2021.018
43. Han Y, Diao Y, Yin Z, et al (2021) Immersive technology-driven investigations on influence factors of cognitive load incurred in construction site hazard recognition, analysis and decision making. Advanced Engineering Informatics 48:101298. https://doi.org/10.1016/j.aei.2021.101298
44. AL-Dhaimesh SH, Taib N (2023) A Review: Investigation of Augmented Reality – BIM Benefits in Design Process in Aec Industry. Informatica 47:111–126. https://doi.org/10.31449/inf.v47i5.4671
45. Yang J, Wilde A, Menzel K, et al (2023) Computer Vision for Construction Progress Monitoring: A Real-Time Object Detection Approach. Computer Vision and Pattern Recognition 1–15. https://doi.org/10.48550/arXiv.2305.15097

https://doi.org/10.36253/tema-16926

46. Kim J (2020) Visual Analytics for Operation-Level Construction Monitoring and Documentation: State-of-the-Art Technologies, Research Challenges, and Future Directions. Frontiers in Built Environment 6:1–20. https://doi.org/10.3389/fbuil.2020.575738
47. Paneru S, Jeelani I (2021) Computer vision applications in construction: Current state, opportunities & challenges. Automation in Construction 132:1–17. https://doi.org/10.1016/j.autcon.2021.103940
48. Wang Y (2024) Research on computer vision application for safety management in construction. Theoretical and Natural Science 30:232–242. https://doi.org/10.54254/2753-8818/30/20241124
49. Roldán López de Hierro AF, Sánchez M, Puente-Fernández D, et al (2021) A Fuzzy Delphi Consensus Methodology Based on a Fuzzy Ranking. Mathematics 9:1–18. https://doi.org/10.3390/math9182323
50. Gutiérrez N, Negrão J, Dias A, Guindos P (2024) Bibliometric Review of Prefabricated and Modular Timber Construction from 1990 to 2023: Evolution, Trends, and Current Challenges. Sustainability 16:1–2[illegible]. https://doi.org/10.3390/su16052134
51. Olawumi TO, Chan DWM, Ojo S, Yam MCH (2022) Automating the modular construction process: A review of digital technologies and future directions with blockchain technology. Journal of Building Engineering 46:1–23. https://doi.org/10.1016/j.jobe.2021.103720
52. Pibal SS, Khoss K, Kovacic I (2022) Framework of an algorithm-aided BIM approach for modular residential building information models. International Journal of Architectural Computing 20:[illegible]77–8[illegible]. https://doi.org/10.1177/14780771221138320
53. F. Yuan P, Wang Y, Gao T, Hu Y (2024) RuiXue Multi-Hall-Human machine collaboration in reciprocal structures. Journal of Chinese Architecture and Urbanism 6:1–18. https://doi.org/10.36922/jcau.1635
54. Ma J, Gomaa M, Bao DW, et al (2022) Printnervi – Design and Construction of a Ribbed Floor System in the Digital Era. Journal of the International Association for Shell and Spatial Structures 63:241–251. https://doi.org/10.20898/j.iass.2022.017
55. Volpe S, Sangiorgio V, Petrella A, et al (2021) Building Envelope Prefabricated with 3D Printing Technology. Sustainability 13:1–13. https://doi.org/10.3390/su13168923
56. Esenarro D, Porras E, Ventura H, et al (2024) Use of Digital Tools (Wikihouse System) in Multi-Local Social Housing. Sustainability 16:1–22. https://doi.org/10.3390/su16083231
57. Piaia E, Turillazzi B, Di Giulio R, Sebastian R (2024) Advancing the Decarbonization of the Construction Sector: Lifecycle Quality and Performance Assurance of Nearly Zero-Energy Buildings. Sustainability 16:1–19. https://doi.org/10.3390/su16093687
58. Wang X, Wang S, Song X, Han Y (2020) IoT-Based Intelligent Construction System for Prefabricated Buildings: Study of Operating Mechanism and Implementation in China. Applied Sciences 10:1–18. https://doi.org/10.3390/app10186311
59. Bataglin FS, Formoso CT, Viana DD (2024) Slack Categories for Managing Risks in the Delivery and Assembly of Engineer-to-Order Prefabricated Building Systems. IEEE Transactions on Engineering Management 71:14032–14045. https://doi.org/10.1109/TEM.2024.3436563
60. Dindorf R, Wos P (2024) Challenges of Robotic Technology in Sustainable Construction Practice. Sustainability 16:1–26. https://doi.org/10.3390/su16135500
61. Chang R, Antwi-Afari MF (2023) Critical success factors for implementing 3D printing technology in construction projects: academics and construction practitioners' perspectives. Construction Innovation: Information, Process, Management 25:843–866. https://doi.org/10.1108/CI-04-2023-0060
62. Helm V (2014) In-Situ Fabrication: Mobile Robotic Units on Construction Sites. Architectural Design 84:100–107. https://doi.org/10.1002/ad.1763
63. Loveridge R, Coray T (2017) Robots on construction sites: The potential and challenges of on-site digital fabrication. Science Robotics 2:. https://doi.org/10.1126/scirobotics.aan3674
64. Pedersen J, Neythalath N, Hesslink J, et al (2020) Augmented drawn construction symbols: A method for ad hoc robotic fabrication. International Journal of Architectural Computing 18:254–269. https://doi.org/10.1177/1478077120943163
65. Mechtcherine V, Nerella VN, Will F, et al (2019) Large-scale digital concrete construction – CONPrint3D concept for on-site, monolithic 3D-printing. Automation in Construction 107:102933. https://doi.org/10.1016/j.autcon.2019.102933
66. Dörfler K, Dielemans G, Lachmayer L, et al (2022) Additive Manufacturing using mobile robots: Opportunities and challenges for building construction. Cement and Concrete Research 158:1–13. https://doi.org/10.1016/j.cemconres.2022.106772
67. Oke AE, Aliu J, Fadamiro P, et al (2024) Robotics and automation for sustainable construction: microscoping the barriers to implementation. Smart and Sustainable Built Environment 13:625–643. https://doi.org/10.1108/SASBE-12-2022-0275
68. Bier H, Becker M (2024) Dialogues on Architecture #6. SPOOL 11:81–86. https://doi.org/10.47982/spool.2024.1.061
69. Bielienkova O, Novak Y, Matsapura O, et al (2022) Improving the Organization and Financing of Construction

https://doi.org/10.36253/tema-16926

Project by Means of Digitalization. International Journal of Emerging Technology and Advanced Engineering 12:108–115. https://doi.org/10.46338/ijetae0822_14

70. Wang K, Zhang C, Guo F, Guo S (2022) Toward an Efficient Construction Process: What Drives BIM Professionals to Collaborate in BIM-Enabled Projects. Journal of Management in Engineering 38:. https://doi.org/10.1061/(ASCE)ME.1943-5479.0001056
71. Carrasco-Beltrán D, Serrano-Sierra A, Cuervo R, et al (2024) Digital Transformation in University Architecture: Optimizing Construction Processes and User Experience through CAMPUS 2.0 at Pontificia Universidad Javeriana. Buildings 14:1–19. https://doi.org/10.3390/buildings14103095
72. Sampaio AZ, Constantino GB, Almeida NM (2022) 8D BIM Model in Urban Rehabilitation Projects: Enhanced Occupational Safety for Temporary Construction Works. Applied Sciences 12:1–21. https://doi.org/10.3390/app122010577
73. Disney O, Roupé M, Johansson M, Domenico Leto A (2024) Embracing BIM in its totality: a Total BIM case study. Smart and Sustainable Built Environment 13:512–531. https://doi.org/10.1108/SASBE-06-2022-0124
74. Jowett B, Edwards DJ, Kassem M (2024) Field BIM and mobile BIM technologies: a requirements taxonomy and its interactions with construction management functions. Construction Innovation 24:134–16[illegible] https://doi.org/10.1108/CI-07-2022-0160
75. Koseoglu O, Nurtan-Gunes ET (2018) Mobile BIM implementation and lean interaction on construction site: A case study of a complex airport project. Engineering, Construction and Architectural Management 25:1298–1321. https://doi.org/10.1108/ECAM-08-2017-0188
76. Huang T, Kong CW, Guo HL, et al (2007) A virtual prototyping system for simulating construction processes. Automation in Construction 16:576–585. https://doi.org/10.1016/j.autcon.2006.09.007
77. Si J, Wan C, Hou L, et al (2023) Self-Organizing Optimization of Construction Project Management Based on Building Information Modeling and Digital Technology. Iranian Journal of Science and Technology, Transactions of Civil Engineering 47:4135–4143. https://doi.org/10.1007/s40996-023-01121-x
78. Feng Z, Sha Y, Liu M (2023) Application of BIM in the Design and Construction of Fabricated Buildings. Computer-Aided Design and Applications 20:1–12. https://doi.org/10.14733/cadaps.2023.S7.1-12
79. Darko A, Chan APC, Yang Y, Tetteh MO (2020) Building information modeling (BIM)-based modular integrated construction risk management – Critical survey and future needs. Computers in Industry 123:1–15. https://doi.org/10.1016/j.compind.2020.103327
80. Bariczová G, Erdélyi J, Honti R, Tomek L (2021) Wall Structure Geometry Verification Using TLS Data and BIM Model. Applied Sciences 11:1–20. https://doi.org/10.3390/app112411804
81. Elghaish F, Matarneh ST, Alhusban M (2022) The application of “deep learning” in construction site management: scientometric, thematic and critical analysis. Construction Innovation: Information, Process, Management 22:580–603. https://doi.org/10.1108/CI-10-2021-0195
82. Tibaut A, Zazula D (2018) Sustainable management of construction site big visual data. Sustainability Science 13:1311–1322. https://doi.org/10.1007/s11625-018-0595-9
83. Choi W, Na S, Heo S (2024) Integrating Drone Imagery and AI for Improved Construction Site Management through Building Information Modeling. Buildings 14:1–27. https://doi.org/10.3390/buildings14041106
84. Murti CK, Muslim F (2023) Relationship between Functions, Drivers, Barriers, and Strategies of Building Information Modeling (BIM) and Sustainable Construction Criteria: Indonesia Construction Industry. Sustainability 15:1–[illegible]. https://doi.org/10.3390/su15065526
85. Salem T, Dragomir M (2022) Options for and Challenges of Employing Digital Twins in Construction Management. Applied Sciences 12:1–10. https://doi.org/10.3390/app12062928
86. Visairsakul B, Damrianant J (2023) A Review of Building Information Modeling and Simulation as Virtual Representations Under the Digital Twin Concept. Engineering Journal 27:11–27. https://doi.org/10.4186/ej.2023.27.1.11
87. Wang Y, [illegible], Xiong J, et al (2024) Digitization impact on future housing building industry mode. Journal of Building Engineering 96:1–28. https://doi.org/10.1016/j.jobe.2024.110202
88. Al-Ruwaishedi MR, Khraisat D, Taib N, Azzam E (2024) In-Depth Survey on Using BIM Digital Technologies in Jordanian Architectural Industry. Civil Engineering and Architecture 12:2744–2754. https://doi.org/10.13189/cea.2024.120418
89. Sidani A, Matoseiro Dinis F, Duarte J, et al (2021) Recent tools and techniques of BIM-Based Augmented Reality: A systematic review. Journal of Building Engineering 42:1–13. https://doi.org/10.1016/j.jobe.2021.102500
90. Chen X, Chang-Richards AY, Pelosi A, et al (2021) Implementation of technologies in the construction industry: a systematic review. Engineering, Construction and Architectural Management 29:3181–3209. https://doi.org/10.1108/ECAM-02-2021-0172
91. Chen S-Y, Zhang J-X, Ni Q-C, et al (2022) Data-Driven Platform Framework for Digital Whole-Process Expressway Construction Management. Front Neurosci 16:1–22. https://doi.org/10.3389/fnins.2022.891772
92. Cucurnia A (2024) Devices for digital construction site management. RACK – Charging Station and Doc –

https://doi.org/10.36253/tema-16926

Construction Site Operational Desk: Dispositivi per la gestione digitale del cantiere. RACK – Stazione di Ricarica e Doc – Desk Operativo di Lavoro. Valori e Valutazioni 35:145–161. https://doi.org/10.48264/VVSIEV-20243509

93. Malykhin M, Pylypchuk O, Tytok V, et al (2024) Digital standards and protocols for interoperability in construction systems and methodologies. AIS - Architecture Image Studies 5:52–69. https://doi.org/10.48619/AIS.V5I2.998

94. Fobiri G, Musonda I, Muleya F (2022) Reality Capture in Construction Project Management: A Review of Opportunities and Challenges. Buildings 12:1–21. https://doi.org/10.3390/buildings12091381

95. Hartmann S, Gossmann D, Kalmuk S, Klemt-Albert K (2023) Optimizing Interfaces of Construction Processes by Digitalization Using the Example of Hospital Construction in Germany. Buildings 13:1–18. https://doi.org/10.3390/buildings13061421

96. Terentyeva I, Lunev A, Kashina S, et al (2020) The Virtual Construction Site: Knowledge Management in Virtual Environments. International Journal of Emerging Technologies in Learning (iJET) 15:81–95. https://doi.org/10.3991/ijet.v15i13.14655

97. Gledson B, Rogage K, Thompson A, Ponton H (2024) Reporting on the Development of a Web-Based Prototype Dashboard for Construction Design Managers, Achieved through Design Science Research Methodology (DSRM). Buildings 14:1–20. https://doi.org/10.3390/buildings14020335

98. Schranz C, Urban H, Gerger A (2021) Potentials of Augmented Reality in a BIM-based building submission process. Journal of Information Technology in Construction 26:441–457. https://doi.org/10.36680/j.itcon.2021.024

99. Amici C, Rotilio M, Berardinis PD, Cucchiella F (2022) Framework for Computerizing the Processes of a Job and Automating the Operational Management on Site—A Case Study of Demolition and Reconstruction Construction Site. Buildings 12:1–17. https://doi.org/10.3390/buildings12060800

100. Fazel A, Adel A (2024) Enhancing construction accuracy, productivity, and safety with augmented reality for timber fastening. Automation in Construction 166:1–17. https://doi.org/10.1016/j.autcon.2024.105596

101. Takva Ç, Cudzik J, Zeynep Yİ Digitalization of Building Site Management in the Construction Industry. International Journal of Sustainable Construction Engineering and Technology 14:171–193. https://doi.org/10.30880/ijscet.2023.14.04.014

102. Geiger M, Hock D, Nübel K (2023) Development of a Novel Production Model for Labour Productivity: Modular Construction Toolkit Design. Buildings 13:1–25. https://doi.org/10.3390/buildings13112887

103. Zainon N, Lun Wei G, Mohamed Zaid N, et al (2019) Developing a Framework for- Life Cycle Assessment of Construction Materials through Building Information Modelling (BIM). International Journal of Innovation, Creativity and Change 10:253–276

104. Chen H (2023) Analysis of Construction Industry Information Management to Improve Project Management. JLISS 10:249–263. https://doi.org/10.33168/JLISS.2023.0319

105. Urban H, Fischer S, Schranz C (2024) Adapting to an OpenBIM Building Permit Process: A Case Study Using the Example of the City of Vienna. Buildings 14:1–24. https://doi.org/10.3390/buildings14041135

106. Getuli V, Giusti T, Capone P, et al (2018) A Project Framework to Introduce Virtual Reality in Construction Health and Safety. IN BO 9:166–175

107. Liu H, Song J, Wang G (2021) A Scientometric Review of Smart Construction Site in Construction Engineering and Management: Analysis and Visualization. Sustainability 13:1–19. https://doi.org/10.3390/su13168860

108. Hajirasouli A, Banihashemi S, Drogemuller R, et al (2022) Augmented reality in design and construction: thematic analysis and conceptual frameworks. Construction Innovation: Information Process Management 22:412–443. https://doi.org/10.1108/CI-01-2022-0007

109. Jeong H, Ahn H, Shin D, Choi C (2019) Comparison the Mapping Accuracy of Construction Sites Using UAVs with Low-Cost Cameras. Korean J Remote Sens 35:1–13. https://doi.org/10.7780/kjrs.2019.35.1.1

110. Nguyen LHT, Lee Y-J, Park M-W (2024) Augmented Reality Framework for Retrieving Information of Moving Objects on Construction Sites. Buildings 14:1–20. https://doi.org/10.3390/buildings14072089

111. Manning CG (2023) Technology Readiness Levels. In: NASA. https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/. Accessed 10 Feb 2025

https://doi.org/10.36253/tema-16926