UTS ePRESS

Construction Economics and Building

Vol. 24, No. 3
July 2024

Citation: Cakmak, P. I., Akturk, B. 2024. An In-Depth Investigation of Digital Construction Technologies From a Building Economics Perspective. *Construction Economics and Building*, 24:3, 40–75. https://doi.org/10.5130/AJCEB.v24i3.8835

ISSN 2204-9029 | Published by UTS ePRESS | https://epress.lib.uts.edu.au/journals/index.php/AJCEB

RESEARCH ARTICLE

An In-Depth Investigation of Digital Construction Technologies From a Building Economics Perspective

Pinar Irlayici Cakmak*, Berkay Akturk

Faculty of Architecture, Istanbul Technical University, Istanbul, Türkiye

Corresponding author: Pinar Irlayici Cakmak, Faculty of Architecture, Istanbul Technical University, irlayici@itu.edu.tr

DOI: https://doi.org/10.5130/AJCEB.v24i3.8835
Article History: Received 26/09/2023; Revised 29/12/2023; Accepted 23/01/2024; Published 01/07/2024

Abstract

While initial costs in building economics cover a small portion of the costs incurred during its life cycle, most occur in construction, operation, and subsequent processes. Despite its numerous contributions to building economics, the construction industry is slowly adapting to digital technologies. To overcome the barriers and crown the assets with their proper management, dynamic applications of digital tools and techniques of Industry 4.0 need to emerge in the construction industry. Therefore, this study aims to present an integrative approach that combines quantitative and qualitative analysis techniques to critically review the available literature on the potential contributions of digital construction technologies to building economics through the post-design phases of the life cycle. The primary focus of the investigation is how digital technologies can overcome prevalent problems and how they can impact building economics. The study contributes to the field by providing an awareness that will inform researchers and practitioners of the trends, gaps, and more profound exchange of ideas in future research efforts.

Keywords

Building Economics; Construction; Digital Technologies; Post-Design Phases

DECLARATION OF CONFLICTING INTEREST The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. **FUNDING** The author(s) received no financial support for the research, authorship, and/or publication of this article.

UTS ePRESS

JEL Classification

L74 Construction; O32 Management of Technological Innovation and R&D; Q55 Technological Innovation

Introduction

The global economy depends heavily on the construction industry, which contributed around 6% of the world's GDP in 2018 and is predicted to grow to about 14.7% by 2030 (Ye, Zeng and König, 2022). A 1% increase in productivity globally might reduce building costs by $100 billion annually, improving a nation's competitiveness and sustainable development (Craveiro, et al., 2019). However, the industry is seen as primarily low-tech, still reliant on traditional techniques, with a poor reputation for performance and productivity (Choudhry, 2017; Li, Greenwood and Kassem, 2019; Opoku, et al., 2021). Many industries have significantly improved by adopting emerging technologies to increase efficiency and productivity (Lu, et al., 2015; Li, Greenwood and Kassem, 2019). Although digital technologies have significantly transformed various industries, the construction industry has still been criticised for being one of the least digitised industries since it shows a slower adoption of innovative tools (Craveiro, et al., 2019; Jang, et al., 2021; Ye, Zeng and König, 2022; Jiang, Messner and Matts, 2023).

Digital technologies have recently proliferated in the construction industry, and digitisation has become an attractive subject for the construction research discipline. While numerous studies have been conducted on integrating digital technologies into building life cycle processes, most of them have concentrated on the uses and benefits through the design phase (Opoku, et al., 2021; Ozturk, 2021; Shahzad, et al., 2022). Since digital technologies significantly contribute to building economics, further research is needed to review the potential of digital construction technologies from the standpoint of building economics.

Correspondingly, this paper aims to provide further research by presenting an integrative approach by critically reviewing published research on digital construction from a building economics perspective. The paper investigates how digital technologies can overcome prevalent problems and how they can impact building economics. The findings present a quantitative evaluation of trends, keywords, clusters and citations of selected publications. Followingly, digital technologies are categorised and analysed under eight main groups: "AI and data processing technologies", "building information modelling", "IoT devices and data communication technologies", "wearable technologies", "augmented reality", "robotics", "image-based technologies", and "blockchain". The paper demonstrates the contribution of the analysed digital construction technologies to building economics through the post-design stages of the life cycle by revealing their areas of use, the problems they eliminate and the positive outcomes they provide. The outcomes of the paper are expected to contribute to construction professionals and academicians by presenting a comprehensive guideline for digital technologies considering building economics through the post-design phases. This paper can also be a reference point by providing awareness of potential directions for future research efforts.

The remainder of this paper is organised as follows: in the next section, an overview of the interaction between the construction industry and industry 4.0 technologies is presented. Next, the research methodology and data collection setup are described. Results and discussions are then presented together for both bibliometric and content analysis. While the first part presents the findings of trends of publications, keyword, cluster, and citation analyses, the second part presents the in-depth investigation of digital technologies in categories to make it more understandable and readable for readers. Finally, conclusions are drawn, and future research directions are outlined.

Digital construction technologies

The main idea of the current industrial revolution, also known as Industry 4.0, is linking physical settings with digital ecosystems (Sepasgozar, 2021; Akturk, 2022). The digital technologies accompanying Industry 4.0, such as the Internet of Things, machine learning, cloud computing, big data, robotics, virtual and augmented reality and many others, have the capability of transforming the operational productivity of industries universally (Oke, et al., 2023a; Oke, et al., 2023b). However, in the construction industry, lack of digital skills and reluctance to implement new technologies can result in cost overruns, inadequate project quality, delays, wrong decisions, and limited productivity performance (Singh, et al., 2023). The entire construction workforce spends over 35% of their working time on non-productive activities like scrutinizing project information, resolving conflicts, waiting for instructions or squandering time on poorly planned assignments, leaving the industry stuck at a 43% productivity rate and causing it to fall behind other industries such as manufacturing, which has more than twice the productivity at a rate of 88% (Slaton, Hernandez and Akhavian, 2020).

To overcome longstanding construction industry challenges such as schedule conflicts and budget overruns, integrating the right Industry 4.0 tools and technologies can become digital construction technologies and significantly increase productivity and safety throughout a project (Slaton, Hernandez and Akhavian, 2020). For instance, advances in image-based and sensor-based technologies such as global positioning systems, radio frequency identification, ultra-wideband, scanners, cameras, and inertial measurement units have begun to replace human observers of the industry, which are dependent on manual inspection and evaluation (Sanhudo, et al., 2021). Thus, by automating tasks, site safety increases, costs decrease, planning is supported, field monitoring improves, errors are eliminated, quality increases, and resources are optimized (Oke, et al., 2023a). Along with these, artificial intelligence, data processing and communication technologies, building information modelling, the Internet of Things, wearables, augmented reality, and robotics are other digital construction technologies that have various application areas in the industry and will be discussed in this paper.

Research methodology

This paper adopts an integrative approach consisting of bibliometric analysis and content analysis to assess and examine the existing literature on the potential of digital construction technologies from the viewpoint of building economics. The research exclusively focused on the analysis of the literature of digital construction technologies. No human participants were involved in the research process, and thus, Human Research Ethics Clearance (HREC) was not applicable. The study employed bibliometric analysis and content analysis to gather and analyze data. Bibliometric analysis helps quantitatively investigate the literature using mathematical and statistical methods (Wang, et al., 2021). The following step involves conducting a content analysis that adds a qualitative layer to the quantitative analysis using bibliometric data (Rodrigo, et al., 2023). Accordingly, the research methodology process applied in this paper can be seen in Figure 1.

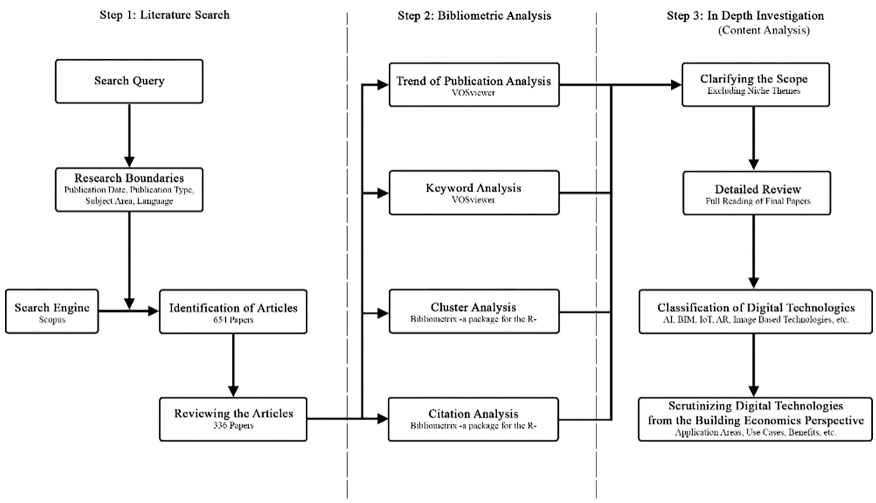

Figure 1. The research methodology process

Among several data sources, Scopus was selected for data acquisition since it performs better with broader coverage of scientific publications than other databases (Falagas, et al., 2008; Chadegani, et al., 2013; Akinlolu, et al., 2022). A comprehensive search was conducted under the "Title/Abstract/Keyword" field, with the search query consisting of three parts: (1) construction industry, (2) building economics, and (3) digital technologies. The search query can be seen in Table 1. Similar keywords referring to building economics were identified and searched with the help of Boolean operators "AND" and "OR". Likewise, a comprehensive list of digital technologies that cover a broad range of techniques was involved in the query (adapted from Dobrucali, et al., 2023). The * character was used to represent any number of characters to cover spelling variations and related words.

Table 1. The search query

(1) construction industry	("construction industry")
(2) building economics	("financ*" OR "investment" OR "resourc*" OR "material" OR "labo*r" OR "equipment" OR "cost" OR "time" "econom*" OR "productivity" OR "efficiency" OR "monetar*")
(3) digital technologies	("information technolog*" OR "information and communication technology" OR "digital tech*" OR "digiti*ation" OR "industry 4.0" OR "construction 4.0" OR "construction tech*" OR "automation" OR "building automation system" OR "autonomous construction" OR "building information model*" OR "BIM tech*" OR "digital twin" OR "virtual twin" OR "robot*" OR "robotic*" OR "simulation" OR "virtual reality" OR "augmented reality" OR "augmented virtual*" OR "immersive media" OR "mixed reality" OR "internet of thing*" OR "big data" OR "3D print*" OR "wearable device*" OR "e-hard hat" OR "artificial intelligence" OR "machine learn*" OR "deep learn*" OR "cloud tech*" OR "cloud comput*" OR "blockchain" OR "ultra wideband" OR "ultra-wide band" OR "ultra-wideband" OR "geographic information system*" OR "global position* system*" OR "remote sens*" OR "sens* tech*" OR "sensor" OR "wireless tech*" OR "wireless network" OR "wireless local area network" OR "wireless sensor network" OR "WiFi" OR "internet of service*" OR "web service*" OR "automatic identification system*" OR "4D visual* tech*" OR "photogrammetry" OR "image process*" OR "video" OR "camera" OR "virtuali*ation" OR "barcod*" OR "mobile comput*" OR "bluetooth" OR "unmanned aerial" OR "drone*" OR "laser detection and ranging" OR "laser scan*" OR "3D scan*" OR "point cloud" OR "radio frequency identification" OR "4D model*" OR "real-time" OR "real time" OR "early warn*" OR "object recognition" OR "object identif*" OR "mobile device*" OR "cyber physical system" OR "embedded system*")

The research boundaries were determined concerning the publication date, the publication type, the subject area, and the publication language. Since the construction industry shows a slow adoption of digitalisation and is at a rather beginner stage in applying digital technologies to building life cycle processes, the publication date range was set from 2012 to 2023. The publication type was set to "article", as journal articles are known as the most reliable and significant sources of knowledge (Santos, Costa and Grilo, 2017). All documents with a core subject of building economics but not relevant to digital technologies were left out of the review. The publication language was restricted to English. Accordingly, the search was conducted on the 18th of July 2023, and 654 publications were retrieved from the Scopus database. A preliminary screening was further conducted to remove the publications that were not within the scope of the research. The authors reviewed the titles and abstracts of the 654 publications to ensure that only papers on digital technologies in the construction industry from a building economics perspective were included in the study. After the review, a total of 336 publications remained.

The bibliometric data was downloaded in suitable formats, pre-processed, and modified to suit the analysis with bibliometric tools. Prior to analysis, similar words with different versions were standardised to obtain more precise results. The final files were transmitted to VOSViewer and Bibliometrix R software package tools. These two tools helped to improve the bibliometric analysis by scientifically mapping the existing literature and visually assessing the prominent research outlets.

Results and Discussion

This section presents the findings of analyses performed to address the study's objectives. First, several bibliometric analyses were conducted to reveal the progress of the related studies. Next, an in-depth investigation of key digital technologies was presented based on the content analysis of studies.

BIBLIOMETRIC ANALYSIS

Trend of publications analysis

Figure 2 illustrates the yearly publication trend of publications on digital technologies in the construction industry from a building economics perspective between 2013 and 2023 (until the 18th of July 2023). It can be seen from the graph in Figure 2 that with 20 publications more in 2019 than in 2018, there has been a noticeable increase. Likewise, the number of studies has expanded steadily throughout the following years, and the research subject has generated significant attention in the past three years. It can be noted that the increasing trend is parallel to the advancement and uptake of digital technologies in the construction industry.

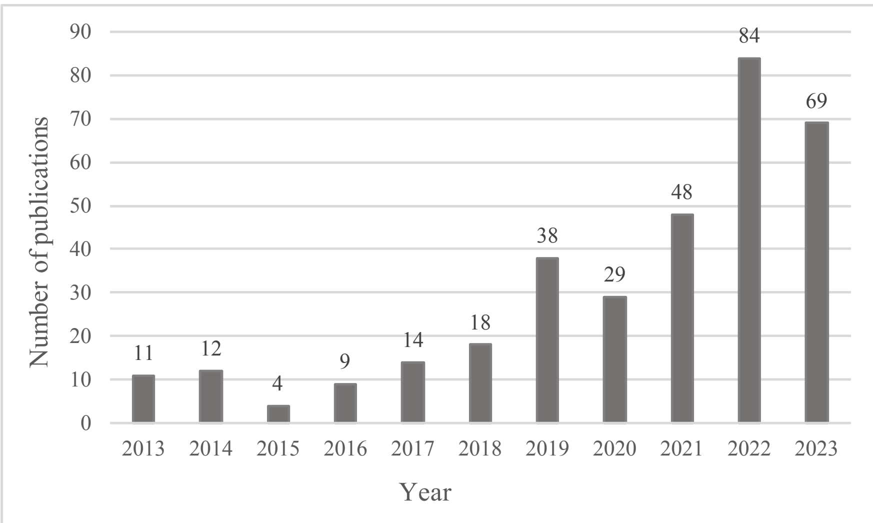

Figure 2. The number of publications by year

Figure 3 displays the top leading journals based on the production over time. These journals have made a substantial contribution by the publication of 52% of the total articles. Automation in Construction has published 26% of all the articles among them. This is followed by Buildings (12.1%), Journal of Building Engineering (10.4%), Engineering Construction and Architectural Management (9.8%), and Journal of Construction Engineering and Management (9.2%).

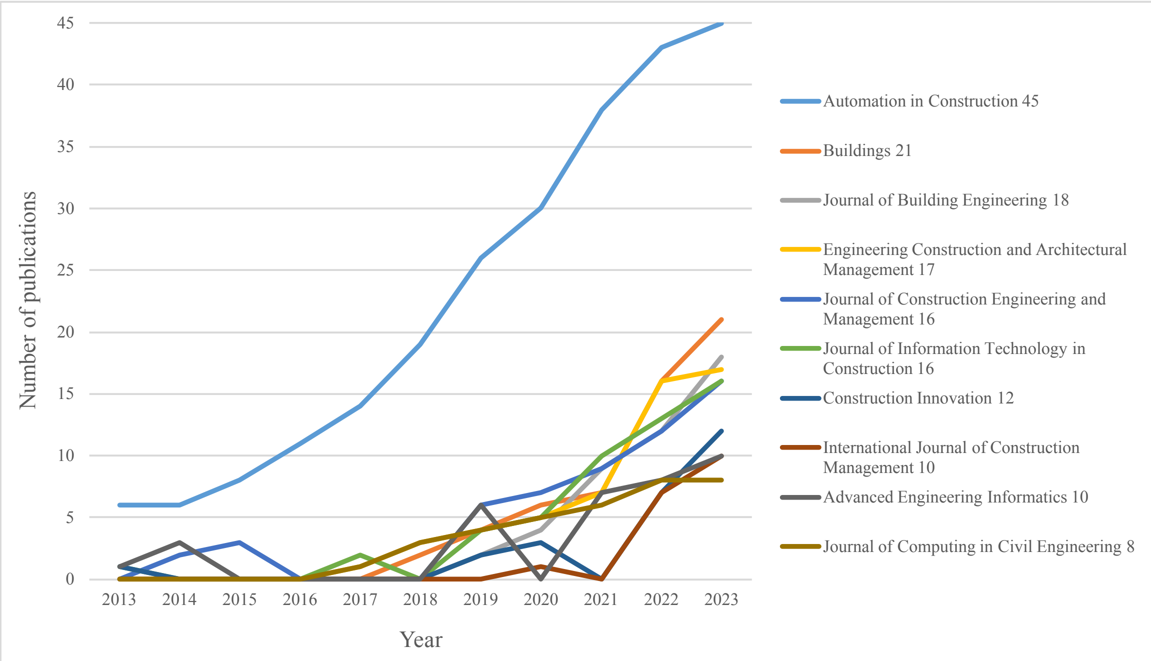

Figure 3. The number of publications by journals

Keyword analysis

Keywords are crucial components in identifying the study's essence and focus. The keyword analysis was conducted to see the frequency of keywords co-occurrence in publications and to determine the main clusters in digital technologies from the viewpoint of building economics research. In the analysis, a total of 1,104 keywords were identified. The analysis was conducted for a minimum threshold of five keywords, and 36 keywords met the threshold. Figure 4 illustrates the keywords co-occurrence map, where the size of the nodes denotes the frequency of occurrences, and the thickness of the links between keywords denotes connections. The most frequently occurring keywords were "building information modelling" (98 occurrences), "construction industry" (39), "construction" (33), "productivity" (25), "construction management" (23), "sustainability" (19), "safety" (15). Seven clusters were identified, each depicted by a different colour.

The data of 36 keywords were tabulated and shown in Table 2, along with their clusters, occurrence values, link strengths and ranks. These keywords indicate research areas that have attracted much attention and are closely related to other keywords. It is not surprising that "building information modelling" ranked first with the highest values since it has become widely accepted in the industry by bringing a new method of collaboration and improving productivity. Due to their presence in the search query, "construction industry", "construction", and "productivity" showed high co-occurrence values. Other high-ranked keywords associated with the practices of digital technologies to contribute to building economics are "blockchain", "machine learning", "construction 4.0", "deep learning", "Internet of things", and "robotics".

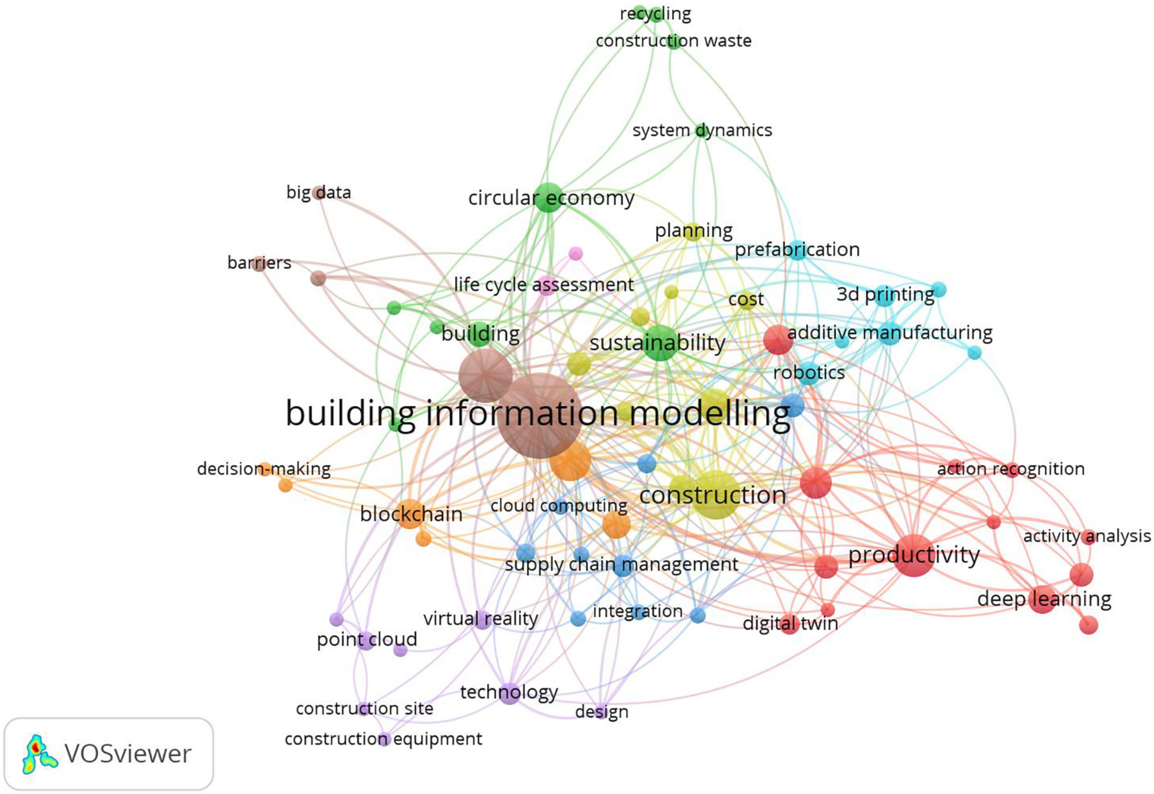

Figure 4. Keywords co-occurrence map

Table 2. Keywords with the highest co-occurrence

Clusters	Keywords	Occurrences	Total link strength	Rank
Cluster 1 (red coded)	artificial intelligence	5	8	31
	augmented reality	5	7	32
	construction	33	52	3
	construction management	23	34	5
	construction safety management	8	6	20
	Internet of things	9	13	14
	machine learning	12	14	11
	safety	15	21	7
Cluster 2 (green coded)	building	9	8	15
	building information modelling	98	90	1
	circular economy	12	16	10
	life cycle assessment	6	4	27
	sustainability	19	31	6
	sustainable construction	5	10	30
	virtual reality	5	4	35

Table 2. continued

Clusters	Keywords	Occurrences	Total link strength	Rank
Cluster 3 (blue coded)	blockchain	13	13	9
	construction 4.0	11	13	12
	construction industry	39	48	2
	innovation	5	7	33
	supply chain management	7	10	24
	technology	7	11	22
Cluster 4 (yellow coded)	computer vision	8	6	21
	deep learning	11	11	13
	digital twin	6	6	26
	energy efficiency	8	10	18
	object detection	5	6	34
	productivity	25	32	4
Cluster 5 (purple coded)	3d printing	7	11	23
	additive manufacturing	8	14	16
	automation	14	22	8
	prefabrication	6	10	25
	robotics	8	9	19
Cluster 6 (cyan coded)	cost	5	14	28
	planning	5	13	29
	simulation	8	14	17
Cluster 7 (orange coded)	point cloud	5	2	36

Cluster analysis

Cluster analysis was done by mapping digital technologies literature based on the keywords via the Bibliometrix R software package tool. As represented in Figure 5, a thematic map was created based on the clusters' degree of development (density) and relevance (centrality). The thematic map was divided into four zones: basic themes, emerging or declining themes, motor themes, and niche themes. Each theme included clusters covering a group of keywords that appeared together. Basic themes covered co-occurrences with a high degree of relevance but a low degree of development, suggesting that the topics are significant and cover general issues from several fields. Not surprisingly, under basic themes, the most frequent keywords appeared as "building information modelling", "construction industry", "construction", "construction management", and "sustainability" in the first cluster. The second cluster included "automation", "construction 4.0", "additive manufacturing", "energy efficiency", and "robotics". Emerging or declining themes specified co-occurrences with low degrees of relevance and development, covering less developed and insignificant topics. The third cluster, including "deep learning", "computer vision", "object detection", and "activity analysis", and the fourth cluster with "point cloud" were positioned under emerging or declining themes. Niche themes had a high degree of development but low relevance, indicating that while they are well-developed, their significance is relatively low. In the fifth cluster, "construction waste" and "recycling" were prevalent under the niche themes. Additionally, "circular economy", "building", "life cycle assessment", "sustainable construction", and "virtual reality" were common keywords under the sixth cluster. Motor themes included co-occurrences with high degrees of development and relevance, indicating significant and well-developed topics in the area. The seventh cluster, under motor themes, covered the most frequent keywords as "blockchain", "supply chain management", "innovation", "cloud computing", and "smart contract". The last cluster focused on "productivity", "machine learning", "action recognition", and "accelerometer".

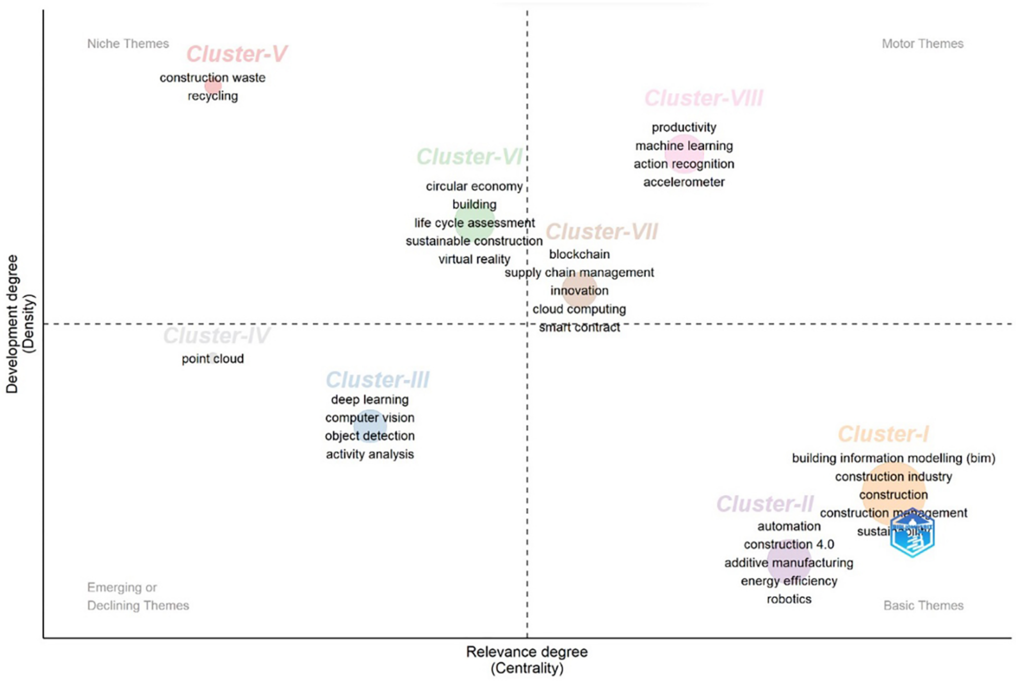

Figure 5. Keywords cluster analysis

Citation analysis

To understand the evolution of the research area, it is essential to discover the papers with the highest impact that influenced later studies. Accordingly, a citation analysis was conducted to identify the leading publications in the field. The average number of citations of 336 publications was calculated as 4.41. Table 3 listed the most influential ten papers and their research focus based on the number of total citations. As shown, the most influential publication was "*Building Information Modeling (BIM) partnering framework for public construction projects*" by Porwal and Hewage (2013), with 28.9 citations per year.

IN-DEPTH INVESTIGATION OF DIGITAL TECHNOLOGIES

A content analysis was conducted by adding a qualitative layer to the bibliometric analysis to investigate the digital technologies in depth. First, the 336 publications were grouped based on the bibliometric

UTS ePRESS

Table 3. The most influential papers based on citations

Author(s) & Year	Publication title	Journal	Research focus	TC	TC/Y
Porwal and Hewage (2013)	Building Information Modeling (BIM) partnering framework for public construction projects	Automation in Construction	Proposes a BIM partnering-based public procurement framework to ensure best value in construction projects	318	28.9
Li, Greenwood and Kassem (2019)	Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases	Automation in Construction	Analyses the current state of DLT intending to develop a coherent approach to support its adoption in the construction industry	265	53.0
Camacho, et al. (2018)	Applications of additive manufacturing in the construction industry–A forward-looking review	Automation in Construction	Provides a review and identifies the trend of AM processes, discusses related methods of implementing AM and potential advancements of AM	227	37.8
de Soto, et al. (2018)	Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall	Automation in Construction	Provides a case study of additive dfab using on-site robotic fabrication technology to map an innovative construction process and evaluate the impact on construction productivity	216	36.0
Golparvar-Fard, Heydarian and Niebles (2013)	Vision-based action recognition of earthmoving equipment using spatio-temporal features and support vector machine classifiers	Advanced Engineering Informatics	Presents a new computer vision-based algorithm for recognizing single actions of earthmoving construction equipment	206	18.7
Mechtcherine, et al. (2019)	Large-scale digital concrete construction–CONPrint3D concept for on-site, monolithic 3D-printing	Automation in Construction	Evaluates the state-of-the-art and presents the CONPrint3D concept for on-site, monolithic 3D-printing	173	34.6

Table 3. continued

Author(s) & Year	Publication title	Journal	Research focus	TC	TC/Y
Akhavian and Behzadan (2016)	Smartphone-based construction workers' activity recognition and classification	Automation in Construction	Evaluates the performance of an activity analysis framework for recognition and classification of various construction worker activities using smartphone built-in sensors	171	21.3
Cheng, et al. (2013)	Automated task-level activity analysis through fusion of real time location sensors and worker's thoracic posture data	Automation in Construction	Presents an original approach to automatically assess labour productivity	151	13.7
Santos, et al. (2019)	Integration of LCA and LCC analysis within a BIM-based environment	Automation in Construction	Explores the potential of BIM as a repository for the LCA and LCC information and how that information should be used for an environmental and economic analysis	146	29.2
Liu, Meng and Tam (2015)	Building information modelling based building design optimization for sustainability	Energy and Buildings	Develops a BIM-based multi-objective optimization model, facilitating designers to identify and choose the optimal carbon emission and cost trade-off design scheme	124	13.7

analysis results. Accordingly, topics that were positioned under niche themes such as "construction waste", "recycling", "circular economy", "building", "life-cycle assessment", "sustainable construction", and "virtual reality" were not included for in-depth analysis. Then, the contents of the papers were qualitatively analysed to investigate digital technologies and how they bring advantages for building economics through the post-design phases of the life cycle. Analysis of studies resulted in the emergence of main categories as: "AI and data processing technologies", "building information modelling", "IoT devices and data communication technologies", "wearable technologies", "augmented reality", "robotics", "image-based technologies", and "blockchain".

AI and Data Processing Technologies Cloud Computing, Edge Computing, Big Data, Machine Learning, Computer Vision, NLP

Artificial intelligence (AI) is the ability of a computer to perform and simulate the processes or tasks that human intelligence is related to. The main advantage of AI is that it will lighten the workload on time-consuming tasks that require a human to think, calculate, and control. (Akturk, 2022). Therefore, various subdomains of AI like machine learning (ML), computer vision (CV), natural language processing (NLP), classification algorithms, fuzzy logic, etc., have started to be scrutinized frequently in the construction industry as well as in many other industries to support decision-making processes, productivity, and efficiency (Singh, et al., 2023). Alternatively, sometimes, to generate a solution in a niche problem area, Rahimian, et al. (2022) implemented an AI model, increasing the quality of communication between employees to improve conflict resolution and team development.

ML and vision-based monitoring systems mainly focus on productivity analysis and safety management by detecting construction objects in a cost-effective manner (Chen, et al., 2022; Fang, et al., 2020; Jiang, Messner and Matts, 2023; Xiao, et al., 2021). Not limited to these two, Singh, et al. (2023) compiled other notable ML applications in the construction literature, such as site monitoring, automated detection, facility management, supply chain management, risk management, and logistics. Moreover, for computer vision applications, Jiang, Messner and Matts (2023) referred to progress monitoring, inspection, and robotic applications. Dong, Chen and Lu (2022) referred to facility management, subsurface mapping, and urban analytics differently. Excavator productivity, for instance, can be calculated in earthmoving operations by detecting excavators and dump trucks (Xiao and Kang, 2020), human motion detection (Chen, Yabuki and Fukuda, 2023), action classification (Lin, Chen and Hsieh, 2021), measuring crew productivity, calculating idling time, and monitoring cyclic operations (Xiao and Kang, 2021) or a real-time warning system can be devised to avoid potential hazards with workers and machinery (Son, et al., 2019). For example, Tian, et al. (2023) monitored the status of machinery and determined their dynamic hazardous proximity zones in real-time, which can be considered a risk and a safety management application. Peng, et al. (2023) developed deep learning, a subset of ML, which reduces construction noise pollution that threatens workers' health, lowers productivity and increases costs due to legal proceedings with neighbours. By using a machine to replace the human eye for measurement and judgment, vision-based AI can manage the safety of construction sites more effectively and smoothly (Zhang, 2021). Computer vision can identify dangerous locations at the construction site (Fang, et al., 2018), control helmets and safety vests, fire detection, and monitor worker posture (Tian, et al., 2023). Yu, et al. (2019a) developed a workload assessment method that automatically collects worker posture data to solve the workload assessment problem at the construction site by integrating sensor technologies. Jacobsen and Teizer (2022) specified applications that directly contribute to the construction economy, such as cost estimation, material selection, success prediction, project selection, automated scheduling and schedule prediction, in addition to the ones above. To exemplify, Liu, et al. (2020) proposed analytics to quantify the life-cycle cost of heavy equipment. Slaton, Hernandez and Akhavian (2020) proposed a more cost-effective and safer method to track resources and activities than other technological options, with the partnership of deep-learning models and sensors. Considering that on-site construction component rehandling works significantly affect construction costs, Li, Luo and Skibniewski (2019) developed a real-time storage area planning and management model that is dynamically updated according to construction activities. Lin, Chen and Hsieh (2021) detected irregular activities to comply with the planned schedule by presenting an image analytics approach to site managers. Sanhudo, et al. (2021) automatically collected and classified worker data by integrating wearable technologies with ML. Automated worker monitoring improves worker productivity and site safety, supports decision-making, and enhances overall project management regarding schedule and resource control.

Neural network applications have been studied to lower costs by reducing skilled human dependency on detecting defects such as cracks, erosion, and concrete delamination in maintenance works (Kruachottikul, et al., 2021). Zhong, et al. (2019) proposed an NN-based classification approach to mitigate the traditional process of quality complaint classification, which is labour-intensive, time-consuming, and error-prone. Wang, et al. (2018) proposed a quality problem predicting model based on text big data generated by the construction process. Hong, et al. (2023), by adapting graph CNNs, reduced the discrepancy between actual and planned schedules. Moreover, NNs are used to solve construction site layout problems by analysing the critical aspects of the site layout and creating advanced construction logistics plans (Li, Luo and Skibniewski, 2019).

NLP applications also support construction management in various aspects in the post-design phases of the building life cycle. Nabavi, et al. (2023) built a platform that simplifies the time-consuming and difficult processes for non-expert stakeholders in the construction phase by extracting information from the BIM model: productivity, coordination, and communication improved. Mo, et al. (2020) reduced processing time and the management team's workload by automating decision-making processes for staff assignment. NLP has safety and risk applications in the literature, such as analysing injury and accident reports, preventing on-site safety failures, avoiding risks, and developing site practices (Nabavi, et al., 2023).

Considering all this data exchange, traditional databases are no longer sufficient, mainly due to the volume of new data sources. Technologies for big data, including cloud storage, NewSQL and NoSQL databases, and distributed file systems (DFS), are currently gaining popularity. In the construction industry, big data can be utilized to enhance project management, safety, energy management, decision-making, resource management, as well as overall cost control and project scheduling (Kruachottikul, et al., 2021). It can monitor progress/performance, track and visualise site conditions, improve resource utilization efficiency, overall time and cost management (Ismail, Bandi and Maaz, 2018), facilitate real-time decision-making, and develop knowledge based on data modelling and analytics (Wang, Hu and Zhou, 2017). Additionally, big data adds new opportunities to the quality management perspective by transforming the decision-making process from being dependent on experienced and judgmental people to a digital process (Ma, et al., 2021). Ma, et al. (2021) proposed a quality inspection model using big data to decrease the workload of managers and time spent on diagnosing and stated four key benefits as follows: (1) overcoming human dependency, (2) cutting down the heavy inspection work, (3) accelerating the quality inspection, and (4) creating a visual quality database. You and Wu (2019) provided supply chain and cost management improvements by proposing an ERP model for managing business and project management data for construction companies with the help of big data technology. As data processing technologies have gained ground in the industry, cloud computing has also attracted the attention of professionals. According to Abedi, et al. (2014), enhanced performance and cost reduction are among the main benefits of cloud computing. The authors also stated that cloud computing can respond to supply-chain problems such as poor planning and scheduling, late lead time, faulty deliveries, and weak on-site coordination. Cloud computing and big data can augment the effectiveness of adopting product-service system solutions for the management of building equipment (Fargnoli, et al., 2019). On the other hand, edge computing has been steadily accepted in industries where decision-making is crucial because it offers real-time responses, lowers ingress bandwidth into the cloud, lowers latency, and reduces data storage and computational burden (Satyanarayanan, 2017). Working on real construction projects and safety accidents, Chen (2020) revealed three main safety application scenarios with edge computing: (1) control of unauthorized site access, (2) monitoring of poor site environment, and (3) prevention of on-site unsafe actions. The author also summarized work in the construction industry literature as video analytics and communication, process documentation, health monitoring of structures and workers, and lastly behavioural analysis, monitoring and assessment of building components.

Building Information Modelling

BIM, serving as a platform and not actually a technology, is a method of using a digital 3D representation of a structure to facilitate the management of itself and all its assets throughout all construction processes. BIM empowers the life-cycle monitoring of buildings by inserting physical and functional attributes of components and systems related to project cost, schedule, specification, and maintenance (Akanmu, Anumba and Ogunseiju, 2021). It provides many benefits through post-design life-cycles of a facility like enhanced quality (Ma, et al., 2021; Rui, Yaik-Wah and Siang, 2021), effective collaboration and communication (Chen, et al., 2023; Honic, et al., 2019), improved clash detection (Moon, Dawood and Kang, 2014), automated, accelerated, efficient and productive processes (Al-Ashmori, et al., 2020; Mesároš, Mandičák and Behúnová, 2022), improved logistics (Karmakar, Singh and Kumar, 2022), safer construction site (Hire, et al., 2021), augmented data management (Wang, 2021), seamless handover (Pakhale and Pal, 2020), and reduced project schedule (Barlish and Sullivan, 2012; Magill, et al., 2022; Martins, et al., 2022a), as well as the control of life-cycle costs and increased profitability (Hire, et al., 2021; Khodabakhshian and Toosi, 2021; Kisel, 2021).

Research in this domain covers various applications that impact building economics. By analysing construction processes, error reduction and efficient practices, streamlining team communication, evaluating resources, and using visual planning for temporary installation and equipment, it saves cost, time, effort and resources, facilitates the planning process, enhances project performance and productivity, and allows for assertive decision-making and on-time delivery (Chen, et al., 2023; Hosny, Ibrahim and Nabil, 2023; Martins, et al., 2022; Mesároš, Mandičák and Behúnová, 2022; Rui, Yaik-Wah and Siang, 2021; Veerendra, et al., 2022). It hosts profitable construction site applications such as automatic cost breakdown structure (Khodabakhshian and Toosi, 2021) and creating quantity take-offs to offer better cost estimates and overcome trade problems and conflicts (Bakchan, Faust and Leite, 2019; Chen, et al., 2023). Stanley and Thurnell (2014) have agreed that 5D BIM improves cost management by providing visualization, collaboration, efficient take-offs and cost planning, risk identification and resolving RFIs as benefits and applications. It also enables an automated scheduling application by evaluating work packages by providing access to the related data of the building components (Park and Cai, 2017; Wang and Rezazadeh Azar, 2019). In addition to offering quality managers applications such as customized checklists, queries, and real-time quality monitoring, it can also be used with GIS to locate and predict damages caused by urban environments, floods, etc. (Ma, et al., 2021). Tao, et al. (2022) developed a BIM-based dynamic site layout planning model, facilitating resource, space and schedule control and reducing transaction costs. BIM detects workspace clashes (Moon, Dawood and Kang, 2014) and offers site route and layout planning (Karmakar, Singh and Kumar, 2022) in the construction site, creating an optimal schedule and logistics management while reducing safety risks. Site layout applications of BIM could also be used to enhance supply chain integration (Li, Luo and Skibniewski, 2019; Santos, et al., 2019). By establishing an integrated construction supply-chain logistics model with 4D BIM, Magill, et al. (2022) optimized the laydown zone options and workforce requirements in the site for materials and equipment, preventing conflicts and avoiding production interruptions. Disputes are prevented in BIM-adapted procurement processes, and the management of pre- and post-contract transaction costs is facilitated (Bean, Mustapa and Mustapa, 2019).

Safety is another significant application area of BIM. It overcomes the limitations of traditional strategies, which are labour-intensive, often time-consuming, and rely on the expertise of professionals (Hire, et al., 2021). It grants hazard recognition, awareness and communication (Kim, Cho and Zhang, 2016; Okpala, Nnaji and Karakhan, 2020), and risk-indicating systems to prevent specific hazards like falling from heights causing monetary and human loss (Rodrigues, Baptista and Pinto, 2022; Tariq, et al., 2023), which empowers key stakeholders to carry out safety standards and make effective and timely decisions.

BIM is also used for facility management applications (Chen, et al., 2018; Nicał and Wodyński, 2016; Zhou, 2022). Becerik-Gerber, et al. (2011) have divided the applications of BIM in the operation and maintenance phase into ten subgroups as follows: locating resources, instant data access, visualization and marketing, maintenance scheduling, inventory management, demolition and reconstruction, emergency management, energy monitoring, and labour education. Application of BIM during the maintenance phase reduces time and labour costs, and the economy of material costs takes place (Kisel, 2021). Fargnoli, et al. (2019) realized the maintenance activities faster and more effectively by including BIM in a maintenance model integrated with the manufacturers of the products and reduced costs for both the service provider and the building manager. Santos, et al. (2019) also stated that if manufacturers integrated economic data into the BIM process, a fluent life-cycle-cost analysis could be carried out automatically. Additionally, Kim, et al. (2023) stated that cost and time-effective facility management can be applied to existing buildings without having technological infrastructure using scan-to-BIM.

IoT Devices and Data Communication Technologies (RFID, Sensors, IMU, GPS, Mobile Devices, Smartphones, UWB, 5G, WiFi, Bluetooth)

In addition to monitoring the condition of the as-built throughout the life cycle of the constructed building, sensors grant access to information about resources and processes employed in the construction (Akanmu, Anumba and Ogunseiju, 2021). IoT represents the network in which physical objects (mechanical or digital tools, living beings, objects, etc.) are supported by sensors connected and exchanged data via the internet or other connection types. Dilakshan, Rathnasinghe and Seneviratne (2021) described "Things" as smart devices connected to a network that conduct most of their communication with little human interaction. Finding their places in construction, operation and maintenance, and demolition phases of the building life cycle, sensors' contribution to the building economy have been extensively studied in the literature.

IoT, sensors and data connection technologies enable construction projects to be completed on time and in good quality through the evaluation of employees' productivity by modelling and classifying activities, achieving a project's best performance (Calvetti, et al., 2020), automated and cost-effective construction resource monitoring (Slaton, Hernandez and Akhavian, 2020), reducing risks and providing accurate risk assessment, active and effective response strategies (Xie and Yang, 2021). For example, John, et al. (2023) proposed a real-time monitoring system of plastic shrinkage from the concrete pouring to its final setting. Thus, the need for more costly repairs is prevented. John, Sarkar and Davis (2022) developed a quality monitoring application that measures concrete compressive strength using Long Range (LoRa) technology, making the dismantling of moulds safer and faster. The authors also mentioned the benefits in the logistics, decision-making, and asset management fields. Kang, et al. (2021) developed a real-time automated monitoring system called MONVID to measure noise, vibration and dust with a sensor network. The authors stated that the system improved project economics compared to conventional measurement systems by providing better reliability, usability, efficiency and superior technical performance. IMU, GPS, WLAN, RFID and UWB-based methods are used as solutions for various aspects such as exposure estimation model (Tian, et al., 2023) and measuring cycle times (Lin, Chen and Hsieh, 2021) for heavy equipment, identifying building components and store a maintenance history (Sanhudo, et al., 2021), a dynamic material layout evaluation model that integrated space and time to improve material accessibility and reduce time waste (Li, Luo and Skibniewski, 2019), and monitoring the location of resources in harsh construction environments (Cheng, et al., 2011). Wang, Hu and Zhou (2017) stated that RFID is mainly used in the construction field to facilitate the management of quality control, inspection and logistics. It allows for the tracking of workers' job status and the progress of operations, the screening of activities by having workers wear RFID-tag-embedded helmets, and the location of tools with embedded tags on construction sites (Sanhudo, et al., 2021). UWB, as an active RFID technology, can create a data fusion system to analyse a worker's productivity and ergonomics and present their real-time location and physiological state (Cheng, et al., 2013a; Sanhudo, et al., 2021). Also, with UWB, ergonomics can be monitored (Akhavian and Behzadan, 2016), and productive and non-productive activities, including wrench, material travelling and rest time can be classified and measured (Cheng, et al., 2013b). Additionally, integrating barcoding and scanners, RFID tags, image processing sensors, and geographic information systems into the supply chain process has been extensively studied in the literature (Adedeji, et al., 2020). For example, RFID provides real-time supply chain visibility through its many advantages, including less inventory, operating and transaction costs, information transparency, increased coordination, and less operational errors (Wang, Hu and Zhou, 2017).

Using BIM as a database allows the IoT to provide managers with real-time quality monitoring and advanced schedule management (Han, et al., 2022). The integration of RFID's ability to track activities and related site spaces with BIM allows site layout plans to be created automatically (Akanmu, et al., 2015). Katiyar and Kumar (2022) used ultrasonic and tilt switch sensors in conjunction with BIM to monitor the project's progress. Moreover, GPS's ability to collect position data of moving equipment for accurate spatial reference also allows site layout planning to be real-time and automated by integration with RFID and BIM (Li, Luo and Skibniewski, 2019). GPS measurement provides project quality improvement, process guarantee and cost control by maintaining information support for decision-makers at every stage of construction (Hu, 2022). Such features are provided through built-in sensors in most smartphones, PDAs, and mobile devices. These devices eliminate delays between outdoor sites and indoor offices and present many use cases. For example, Akhavian and Behzadan (2016) used the data obtained from smartphones with the help of artificial intelligence algorithms to monitor and classify worker activities and reveal the application areas of productivity measurement, progress evaluation, safety and health management. Accelerometers also have much construction research on worker monitoring, equipment monitoring, and safety risk detection (Sanhudo, et al., 2021). Many studies investigating the integration of accelerometers with smartphones have revealed many activity recognition applications that classify and analyse employee movements (Akhavian and Behzadan, 2016). Sangchul and Tae-Hwa (2016) increased productivity with their PDA-based system for more efficient schedule management at the construction site and stated the advantages as follows: raw data and site information are obtained more easily, information is directly delivered to manager for timely decisions, and it improved management in material, workforce and safety manners.

IoT and data processing devices have a wide range of applications in construction safety. The applications of these devices in the construction safety literature can be considered in three categories: (1) tracking and monitoring the location data of workers and machines, (2) identification of unsafe operations and behaviours, and (3) collection of condition data such as the environmental condition of sites or physiological condition of workers (Chen, 2020; Yang, et al., 2020a). IoT is considered a low-cost and affordable safety management technology as it significantly reduces labour costs by overcoming numerous safety managers' needs (Yang, et al., 2020a). It can prevent accidents and improve overall safety management by providing early warnings to managers (Lee, et al., 2020), hazardous area identification (Kim, et al., 2016), and protective personal equipment wearing detection (Yang, et al., 2020b). Also, Tariq, et al. (2023) and Hire, et al. (2021) stated that workers and materials can be positioned using IoT and GPS technologies, thus increasing the effectiveness of monitoring approaches to reduce safety hazards. To avoid struck-by-vehicle accidents, Hallowell, Teizer and Blaney (2010) used RFID and UWB technologies (Kim, et al., 2016). Carbonari, Giretti and Naticchia (2011) created a prototype for proactive safety management and real-time alerting of potential threats using UWB. Lee, et al. (2012) developed a method based on location tracking that alerts workers to dangerous areas. Additionally, Lee, et al. (2014) introduced a location-based system to assist in real-time management and control of direct roots of hazards. Chen, Yabuki and Fukuda (2023) developed a motion recognition method that detects potentially dangerous motions and monitors workers at blind areas of construction sites with deep learning integration. Lee, et al. (2020) proposed an audio-based safety recognition system that monitors and manages various risks and hazards. The system can not only detect events initiating them and ultimately enable the prompt dispatch of a response team but also be used for prevention. In addition to safety, audio signals are also used in productivity measurement by enabling applications such as cost estimating, project scheduling or preparation of preventive actions (Sabillon, et al., 2020) and automated activity analysis to eliminate labour-intensive, time-consuming and error-prone processes (Cheng, et al., 2017).

Wearable Technologies (Wristbands, Exoskeletons, Smartwatches, Smart Helmets, Glasses, Vests)

Wearable devices can be inferred as small electronics worn on a worker's body that is adhered to or concealed within clothing or connected to the PPE of workers (Calvetti, et al., 2020). Wearable technologies have many applications for personalized construction safety monitoring (Awolusi, Marks and Hallowell, 2018). Through efficient data collection, analysis and the provision of real-time information, they can track a worker's position, physiological state, proximity to machinery or equipment, or environmental status and can alert the victim or other parties involved before an injury occurs (Fugate and Alzraiee, 2023). Chen (2020) presented examples of the use of wearable technologies, such as a wristband-type sensor to monitor workers' heart rates to prevent fatigue (Hwang, et al., 2016) and infrared temperature sensors and electroencephalograms to assess their physiological well-being (Aryal, Ghahramani and Becerik-Gerber, 2017; Lee, et al., 2017a). Hwang and Lee (2017) stated that wristbands are feasible and useful for continuously monitoring the physical demands of workers to balance various workloads with a consideration of diverse working situations and individual physical inequalities. The use of wearable devices integrating IMU sensors for construction activity monitoring has gained greater attention, especially for ergonomic assessment of workers, measurement of their motions in various construction activities, and detection of their unsafe postures such as stooping with back bending (Ryu, et al., 2019; Valero, et al., 2016; Yu, et al., 2019b). Yan, et al. (2018) proposed an IMU-based wearable PPE for monitoring and warning rebar workers about the risks associated with their trunks.

Exoskeletons are wearable robots designed to augment the user's body to increase their performance and sturdiness. Zhu, Dutta, and Dai (2021) evaluated how the exoskeleton supports body parts and suggested that more of its benefits in improved productivity and work quality need to be uncovered. For example, an exoskeleton can reduce the physical demand on the wearer's back by reinforcing the hip or lower spine to support the back muscles, which can be a solution for rebar workers who are injured four times more than other workers (Gonsalves, et al., 2021). It allows disabled or injured workers to carry and lift heavier objects on construction sites and helps keep workers out of dangerous areas and complete tasks in less time (Oke, et al., 2023a). Thus, it reduces the task completion time and improves the performance.

Wearable devices' offerings to the construction industry are not limited to the safety field. They also can be used to increase construction productivity and communication (Fugate and Alzraiee, 2023). It is possible to define, analyse and classify construction activities with sensor-integrated wearable devices for automatic productivity analysis (Gong, et al., 2022; Ryu, et al., 2019).

Augmented Reality

Augmented Reality overlays virtual content over the user's view of their physical environment. AR has several use cases for building economics in different building life-cycle phases, such as inspections and monitoring applications, visualization, training and education, and safety (El Asmar, et al., 2021). For example, Karmakar, Singh and Kumar (2022) supported decision-making to plan site layout with comprehensive viewpoint sharing between stakeholders with the help of AR. Katiyar and Kumar (2022) used it to inspect facilities and stated that it is faster and easier than traditional systems. Even that, it allows vision for facilities and installations that are not readily visible, such as wires inside a wall or buried pipelines (Liu and Seipel, 2018). Using AR, Liu and Seipel (2018) were able to alleviate the workload experienced by participants monitoring "as built" progress against "as planned" on site. Ratajczak, Riedl and Matt (2019) proposed a BIM-based AR application enabling site managers to monitor and control construction tasks in distant locations while performing site analysis. The application can detect scheduling anomalies by visualizing construction progress in AR, providing daily progress and performance data of construction work, and information on scheduled tasks. Using AR with the help of AI and UAV technologies, Wang, et al. (2022) proposed a vision-based productivity analysis model for heavy equipment, eliminating time-consuming, tedious and subjective traditional processes and ensuring quality, reducing costs, and optimising construction progress. Tavares, et al. (2019) proposed a robotic integrated AR system that overlays alignment information into the physical environment to help the operator tack weld the beam attachments. To ensure resilience during assembly while also improving the overall productivity and construction quality since the operator no longer needs to rely on error-prone measurement procedures. Additionally, although VR is excluded from the scope of this paper, the uses of mixed reality -which emerged from the joint use of AR and VR- in the production industry can be exemplified as follows: visualizing a building model and hidden in its physical location, visualizing hidden items, augmenting BIM content, monitoring and documentation of construction processes, detection of failures, improving safety, and reducing risk factors (Chalhoub and Ayer, 2018).

Robotics (Automated Heavy Equipment, On-Site General Robots, Robots for Special Tasks)

Robotic solutions that offer process efficiency in a wide range of applications, such as in automating repetitive tasks and working in harsh conditions, have gained importance in industrial scenarios and have attracted the attention of researchers lately. (Tavares, et al., 2019). By using robotics, labour-intensive processes can be automated, creating cost-saving options for construction professionals (Ojha, et al., 2022), increasing safety and reducing reliance on skilled workers (Reichenbach and Kromoser, 2021; Wu, et al., 2023). Robotic applications in construction tasks have proven to be more efficient than traditional approaches in technical and economical manners (Skibniewski, 1988; Najafi and Fu, 2017; de Soto, et al., 2018). Kumar, Balasubramanian and Raj (2016) performed and evaluated the cost and efficiency analysis of various robotic applications, stated that the average time loss of robotic applications was reduced by 57.85%, working costs by 51.67% and rework and scrap costs by 66.76%, and the quality output was improved.

Wu, et al. (2023) divided current robotic studies in the construction industry into three types according to the application scenarios: automation of heavy equipment, special robots designed for specific tasks, and on-site general robots. Oke, et al. (2023a) have compiled some robot application examples and their benefits in the construction literature: demolition robots are more efficient and safe in the demolition of structures and vertical transportation of heavy materials; by using forklift robots, horizontal transportation of heavy objects can be conducted easily, preventing workers from undertaking risky tasks; bricklaying robots also save time, decrease overall construction duration, and enhance the safety, productivity, quality and efficiency of construction sites. Such applications have found their place in the literature. For example, de Soto, et al. (2018) constructed a complex concrete wall with robotics and observed time and cost improvements over traditional processes. Oh, et al. (2009) developed a CV-integrated robotic inspection system to detect and trace the defects (de Soto, et al., 2018). They can be used for site planning, on-site assembly and 3D printing (Melenbrink, Werfel and Menges, 2020). Tehrani, BuHamdan and Alwisy (2022) stated that for on-site installation works, robotic arms are used in applications such as welding, fabricating non-standard structures, installing heavy-duty components, and demolishing works; mobile robots are used for inspection, surveying and pile driving; and special robots are used for specific tasks such as fitting large glass windows on the construction site. The authors also added that these robotic applications prevented the problem of labour shortage by achieving high production quality and workplace safety at the construction site. Kasperzyk, Kim and Brilakis (2017) presented a system that can disassemble and reconstruct a prefabricated structure according to the new design, providing cost and productivity improvements. They also mentioned commercial robotic projects that lay bricks approximately three times faster than humans, constructing whole structures and enabling the production of various forms with layer-by-layer 3D printing. Kumar, Balasubramanian and Raj (2016) used drones for load carrying to reduce time duration and occurrence of accidents. Researchers have automated risky and complex manual construction tasks in their studies, where they developed a robotic beam assembly system (Chu, et al., 2013; Jung, Chu and Hong, 2013).

Bahrin, et al. (2016) used autonomous robots in areas where human effort could be risky, providing precision production with safety, flexibility and versatility while also preventing the problem of death and injury by reducing human intervention. Aghimien, et al. (2020) stated that robotics has become widespread in earth and foundation operations where worker safety cannot be ensured due to excavation work carrying a high safety risk in the construction site due to contact with live electrical underground cables. Jin, et al. (2021), with the help of cameras and robots for rebar binding, reduced the labour requirement and improved safety by reducing the requirement for human quality to access hazardous work areas for binding. Leng, et al. (2023) achieved improved production time, safety and security, the margin of error, and reduced labour costs by proposing a human-robot interaction method combining manual and automated robotic construction advantages.

Image-Based Technologies (Cameras, UAVs, Laser Scanners)

Image-based technologies, also called non-contact sensors, are rapidly increasing to capture daily images or videos from construction sites (Jiang, Messner and Matts, 2023). Additionally, the benefits of these technologies are being extensively researched (Cheng, et al., 2013b) since they can efficiently reduce transportation, safety, communication, and documentation costs in construction projects (Xiao, et al., 2021). For example, by adapting and integrating image-based technologies, Golabchi, et al. (2018) created safer and more productive construction sites by gathering information about job site conditions, worker tasks, and human movements and enabling action recognition. Using cameras, Bügler, et al. (2017) created a 3D point cloud of the site space to analyse and estimate the productivity of heavy equipment by detecting, identifying and tracking resources, which led to quality-insured tasks and a cost-effective and safer workplace. Omar, Mahdjoubi and Kheder (2018) proposed an automated photogrammetry-based approach for monitoring and controlling construction site activities to support decision-makers. Depth cameras, thermopile sensors, and laser scanners are frequently used measurement tools in construction (Yang, et al., 2020b; Zhang and Arditi, 2013). Visual measurement systems can evaluate worker productivity, reduce the time spent, monitor and interpret project status and performance, thus supporting control of cost and schedule (Bügler, et al., 2017). According to Katiyar and Kumar (2022), remote-controlled cameras can be used to monitor projects for outdoor construction, and photogrammetry and LiDAR are better alternatives for automated progress monitoring in terms of cost and time savings. In the past, Bosché (2010) built a 3D point cloud model with laser scanning and compared it with the as-planned BIM model to perform automated progress monitoring. On the other hand, Golparvar-Fard, et al. (2009) combined AR technology for it (Omar, Mahdjoubi and Kheder, 2018). Zhang and Arditi (2013) monitored and calculated construction progress in terms of completion percentage with daily point cloud data placed on the 4D model. Additionally, intending to compare with as-planned models, Braun, et al. (2015) used laser scanners, and Tuttas, et al. (2015) used cameras to create as-built point clouds (Conde, García-Sanz-Calcedo and Rodríguez, 2020). Laser scanning technology also reduces labour costs by automating conventional quality assessment processes based on manual measurements, which are time-consuming, inefficient, subjective, error-prone and unreliable (Guo, Yuan and Wang, 2020; Tang, et al., 2022). Guo, Yuan and Wang (2020) proved that quality assessment can be done cheaper and twice as fast with LS and is economical. Using laser scanners, Lee, et al. (2017b) proposed reverse engineering to prevent reconstruction and ensure quality control. Tehrani, BuHamdan and Alwisy (2022) navigated and scanned indoor construction environments. Yen, Lasky and Ravani (2014) presented a cost-benefit analysis of terrestrial laser scanning for infrastructure applications considering asset management, preservation, maintenance and operational planning. They observed that savings could range from $1.3 million to $6.1 million based on a 6-year life cycle. Vinod, et al. (2022) summarized the applications of image-based technologies in the operation and maintenance phase, such as damage identification, connection tightness control, and comparing as-built and input images. The authors developed a cost-effective, reliable and safer system with processor-supported cameras for checking missing bolts in steel structures. Additionally, they have attracted the academy's attention with many safety applications, such as identifying hazards and the absence of safety tools, tracking resources, and posture analysis, especially with the emergence of the -previously mentioned- CV (Yang, et al., 2020b). By enabling visual tracking, potential struck-by accidents and construction progress and process can be observed, failures of heavy equipment can be checked and their productivity can be analysed, workplace safety can be ensured (Xiao and Zhu, 2018), workers' postures can be analysed to identify any potential ergonomic risks, their skeleton structure can be extracted, and unsafe predefined motions can be detected (Sanhudo, et al., 2021).

UAV-driven automation significantly influences productivity, lowering costs and scheduling overruns (AlRushood, et al., 2023). UAVs can collect high-quality visual data with high-resolution images. Equipped with downward-facing sensors or cameras, such as RGB, thermal or LiDAR, they gather meaningful aerial data quickly (Aiyetan and Das, 2022; Motayyeb, et al., 2023). While UAVs can be used to inspect and survey the construction site, generate progress reports, track resources, and conduct security surveillance, they are also valuable for monitoring hostile site areas where factors such as altitude, radiation and wind can lead to accidents among workers (Aghimien, et al., 2022; Oke, et al., 2023a). Additionally, they can be used for several purposes, which include earthmoving operations, quality control, evaluation of structural damage, risk and safety assessment of the site, and damage assessment. (Aiyetan and Das, 2022; Moon, et al., 2019; Yang, et al., 2020b). They can capture accurate and comprehensive data during construction, and it can be synchronized into BIM and used to manage the entire project (Oke, et al., 2023a). While compiling the roles of UAVs throughout the project life cycle, AlRushood, et al. (2023) also mentioned that -in addition to the above applications- they support supply chain management and provide project data that helps facilitate the final handover. To significantly impact the supply chain and improve inventory accuracy, leading to faster and more cost-effective building projects, the authors also stated that UAVs can be used with IoT, Robotics, AI, and GPS. According to Aiyetan and Das (2022), the most important factor affecting the use of UAVs is their cost savings compared to traditional methods.

As this paper and associated literature commonly state, the integration and co-use of technologies results in new advantages and application areas. Image-based technologies and IoT, two of the three main approaches to construction monitoring, can provide greater benefits when used together (Slaton, Hernandez and Akhavian, 2020). For example, Kim, et al. (2021) and Golabchi, et al. (2016) monitored construction operations for cycle time estimation and efficiency evaluation with motion data gathered from sensors and cameras. Using cameras with artificial intelligence to evaluate labour productivity supports detection accuracy, improves time-consuming and labour-intensive processes (Chen, Yabuki and Fukuda, 2023), and augments visual tracking applications (Xiao and Zhu, 2018). Yu, et al. (2019b) prevented safety risks by making automated and detailed ergonomic assessments of construction workers by integrating image-based technologies and AI. With the integration of point clouds and web technologies with BIM, geometric defects and their locations caused by human errors or technical issues can be observed for improved quality monitoring and a seamless handover process (Ma, et al., 2021). Also, realistic construction progress predictions can be made (Bügler, et al., 2017). Estimating the dimensions with geometry anomalies, measuring and assessing the quality of precast concrete panels, and automatically and precisely assessing the key quality checklist are also possible (Guo, Yuan and Wang, 2020). By using BIM to collect data with Image-based technologies, Conde, García-Sanz-Calcedo and Rodríguez (2020) improved measuring, support decision-making processes and productivity, exceeding 27% in time savings compared to standard CAD methodology. Additionally, Lu and Lee (2017) stated that using image-based technologies to create an as-is BIM model to be used in the operation and maintenance phases is the most cost-effective and economical solution, as well as being convenient, efficient and accurate.

Blockchain

Payment uncertainty adversely affects construction, including excessive costs, schedule delays, project deficits, and cash flow difficulties (Ameyaw, et al., 2023). With this, the industry is frequently criticized for its lack of trust and adversarial relationship, resulting in claims, opportunism, risk aversion, inadequate quality, excessive cost, poor value for money, and other non-productive outcomes (Lu, Wu and Zhao, 2023). Insufficient incentives, poor information sharing, poor traceability, a single point of failure, tampering, privacy leaks, and manual processing are among the problems Lu, Wu and Zhao (2023) listed as things blockchain will fix with trust. They also listed its applications in smart contracts, accounting, procurement and supply chain management, and asset management. Blockchain is an emerging technology that improves information traceability, transparency, security and sustainability (Jiang, et al., 2021).

Mahmoudi, Sadeghi and Naeni (2023) identified ten features for blockchain: (1) cost efficiency, (2) quality management, (3) time efficiency and increased speed, (4) reliability, (5) risk mitigation, (6) sustainability performance, (7) agility and flexibility, (8) transparency and trust, (9) simplicity, and (10) collaboration and communication. These features have led researchers to apply it in various fields and investigate its benefits. For example, according to Gurgun, et al. (2022), blockchain can improve financial issues, make payments easier and secure, and guarantee the validity of long payment plans in the industry. Dakhli, Lafhaj and Mossman (2019) discovered that using blockchain in construction projects can reduce costs by 8.3%. It can enhance real-time information sharing between stakeholders and privacy, secure project records by keeping them across various locations, prevent construction data tampering using hash algorithms, and automate processes using smart contracts (Lu, Wu and Zhao, 2023). Through pre-coded contract terms, payment plans, and automated protocols, blockchain-based smart contracts can automate interactions between parties to a contract and pay suppliers, contractors, and subcontractors in full or in part after the completion of work (Ameyaw, et al., 2023). Yang, et al. (2020) eliminated payment delays and disputes by implementing a smart contract to supply expensive equipment for a construction project. Automating contract processes with blockchain, Gupta and Jha (2023) defined the benefits of the system they developed in six items as follows: (1) transaction time and costs are decreased; (2) security is provided; (3) trust is distributed uniformly among stakeholders; (4) payments are automatic and straightforward dependent on performance; (5) risk distribution is standardised throughout design; and (6) data is trackable in delay claims and concurrent delays. Jiang, et al. (2021) mentioned various blockchain research in construction literature, such as creating a prefabricated supply chain including production, logistics and on-site assembly; improving existing contract management, supply chain management and equipment rental processes; ensuring the security of timely and transparent payment without the burden of administrative costs and trusted intermediaries. The authors also proposed a blockchain platform to support data integration and sharing between stakeholders and address information fragmentation and discontinuity. Ibrahim, et al. (2022) created a prototype that focuses on the payment terms in the building contract as well as guarantees the security of financial transactions. To increase trust and lessen possible delays by frequently monitoring payments and disputes via unchangeable records, Celik, Petri and Rezgui (2023) proposed a blockchain-integrated BIM model to enhance collaboration, eliminate external parties, and ensure that transactions are exceedingly safe, transparent, and trackable.

Conclusion

This paper assessed and examined the existing literature on the potential of digital construction technologies from a building economics perspective. Accordingly, a bibliometric analysis was conducted to quantitatively evaluate the trends, keywords, clusters, and citations of the selected publications. Next, a qualitative content analysis was carried out for the in-depth investigation of digital technologies. Digital construction technologies contributing to building economics were identified, and their use cases and benefits were discovered. Correspondingly, these technologies were grouped under eight categories: "AI and data processing technologies", "building information modelling", "IoT devices and data communication technologies", "wearable technologies", "augmented reality", "robotics", "image-based technologies", and "blockchain".

AI and data processing technologies, which support construction professionals in their decision-making processes, find their place in applications that alleviate the time-consuming workload. This allows those technologies in this category to contribute to the building economy in a broader variety of areas than other digital construction technologies. They stand out by providing a cost-effective way to control productivity and safety on construction sites, with monitoring and real-time evaluation of all types of resources. These technologies mitigate errors and lower costs by reducing human dependency in managing energy, facilities, supply chain and construction sites. Also, various time and cost management techniques and simulations provide project managers with more realistic plans. The second category, BIM, provides a 3D representation of the structure. It creates a database for the implementation of other technologies at first and serves as an effective means of collaboration and communication for all relevant stakeholders. Extensively studied in the literature, 4D and 5D BIM provide better cost estimations, resource, space and schedule control, along with error-reducing opportunities such as conflict detection, creating quantity take-offs, risk identification, optimizing laydown zone options, etc. In addition to the applications, it offers with cost and planning data, safety and facility management are other areas where it stands out with its significant impact on building economics. Third, IoT devices and data collection technologies enable achieving a project's best performance by allowing the observation of project insights by measuring and evaluating the performance of the desired asset. They offer activity and resource monitoring applications for quality, productivity, risk, and logistics management. They improve cost control and schedule management by empowering stakeholders with real-time, error-free measurements and information on construction sites. Using this monitoring feature to prevent accidents that cause significant financial losses on construction sites is presented with comprehensive and practical examples in the literature. Wearable technologies, as the fourth category, have appeared in the construction literature mainly with practices on collecting and analysing data on construction workers' physical and psychological well-being. They improve performance by reducing the completion time of projects and ensuring that employees work in healthy and ergonomic conditions. However, together with augmented reality, considered the fifth category, it can be stated that these technologies have a relatively weaker effect on building economics and are usually used just as an assistive technology in applications where they find a place. Still, due to the vision it provides, AR can be considered a technology that should be kept in the memory of construction practitioners for education, inspection, monitoring, and controlling works. Robotic technologies are a good solution in activities that are unsafe for workers or where safety is difficult to ensure and for providing better quality and time-efficient results. They also provide a significant economic contribution compared to traditional methods in repetitive tasks and lower labour costs in general. This paper examined laser scanners, cameras, drones and all other technologies that use visual data under the seventh category, image-based technologies. With their fulfilling monitoring opportunities, they make significant contributions to building economics with practical applications for measurement, supply-chain, quality assessment, resource tracking, risk and safety assessment. Many researchers have shown that these technologies can effectively reduce costs by evaluating worker productivity, reducing the time spent, supporting schedule control and providing a safer workplace. Finally, blockchain enables contractual and financial processes to occur in a more decent framework where stakeholders can trust each other. It has been observed to significantly contribute to the building economy by eliminating problems that lead to financial and time losses, such as payment uncertainty, privacy leaks, opportunism, poor information sharing, conflicts, and disputes, which we are familiar with in the construction industry.

The analyses showed that digital technologies added value to building economics with their applications, primarily in measuring and monitoring construction resources and activities. These technologies are often used for productivity analysis and health and safety management, such as idle time calculation, motion detection, activity recognition, anomaly detection, resource tracking, and identification of hazardous areas. Consequently, adopting digital technologies instead of traditional methods provides cost-effective and beneficial results in cost control, scheduling, quality assessment and quality control, procurement, logistics, facility and asset management, and risk management.

The most significant part of the literature analysing digital technologies' impact on building economics is aimed at investigating what benefits are obtained from these technologies through the project process. However, it is important and valuable to explore the impact of digital technologies on building economics from a macroeconomic perspective as well. The integration of digital construction technologies discussed in this paper can be considered to be an "engine" for economic development, leading to increased productivity, sustainability, and innovation. Adopting these technologies will result in streamlined workflows, quicker project delivery, cost savings, and improved construction management, which can contribute to economic growth by creating new markets, attracting investment, achieving macroeconomic stability, and enhancing competitiveness on a global scale.

Even though digital technologies are seen as a solution to the non-productive and low-profitable construction industry, their adaptation is relatively slow and mostly concentrated on the early phases of the building life cycle. Therefore, this study fills this gap by contributing to a better understanding of digital construction technologies and their benefits for building economics through the post-design phases by using an integrative approach, which is limited in the literature. Besides, the study's findings are expected to benefit construction professionals and academicians by presenting a comprehensive guideline for digital technologies considering building economics. However, while this study adds to the body of knowledge, attention has to be made to generalising its results as data gathered from only the Scopus database. Further research is needed to explore the challenges and barriers to faster adaptation to digital technologies and to find the best course of action to overcome these barriers. Overall, future research can also focus on the significant impact of digital technologies on building economics from a macroeconomic perspective, emphasizing the transformative effect of digitalisation on economic growth, productivity, and enhanced competitiveness on a global scale.

References

Abedi, M., Rawai, N.M., Fathi, M.S. and Mirasa, A.K., 2014. Cloud computing as a construction collaboration tool for precast supply chain management. *Jurnal Teknologi*, [e-journal] 70(7), pp.1-7. https://doi.org/10.11113/jt.v70.3569

Adedeji, A.O., Abraham Yewande, S. and Oluwafikunmi, A., 2020. Web-based material requisition system in the supply chain of construction businesses. *International Journal of Electrical and Computer Engineering*, [e-journal] 11(2), pp.1531-38. https://doi.org/10.11591/ijece.v11i2.pp1531-1538

Aghimien, D.O., Aigbavboa, C.O., Oke, A.E. and Thwala, W.D, 2020. Mapping out research focus for robotics and automation research in construction-related studies: A bibliometric approach. *Journal of Engineering, Design and Technology*, [e-journal] 18(5), pp.1063-79. https://doi.org/10.1108/JEDT-09-2019-0237

Aghimien, D., Ikuabe, M., Aliu, J., Aigbavboa, C., Oke, A.E. and Edwards, D.J, 2022. Empirical scrutiny of the behavioural intention of construction organisations to use unmanned aerial vehicles. *Construction Innovation*, [e-journal]. https://doi.org/10.1108/CI-04-2022-0088

Aiyetan, A.O. and Das, D.K, 2022. Use of drones for construction in developing countries: Barriers and strategic interventions. *International Journal of Construction Management,* [e-journal]. https://doi.org/10.1080/15623599.2022.2108026

Akanmu, A., Olatunji, O., Love, P.E.D., Nguyen, D. and Matthews, J., 2015. Auto-generated site layout: an integrated approach to real-time sensing of temporary facilities in infrastructure projects. *Structure and Infrastructure Engineering*, [e-journal] 12(10), pp.1243-55. https://doi.org/10.1080/15732479.2015.1110601

Akanmu, A.A., Anumba, C.J. and Ogunseiju, O.O., 2021. Towards next generation cyber-physical systems and digital twins for construction. *Journal of Information Technology in Construction*, [e-journal] 26, pp.505-25. https://doi.org/10.36680/j.itcon.2021.027

Akhavian, R. and Behzadan, A.H., 2016. Smartphone-based construction workers' activity recognition and classification. *Automation in Construction,* [e-journal] 71, pp.198-209. https://doi.org/10.1016/j.autcon.2016.08.015

Akinlolu, M., Haupt, T.C., Edwards, D.J. and Simpeh, F., 2022. A bibliometric review of the status and emerging research trends in construction safety management technologies. *International Journal of Construction Management,* [e-journal] 22(14), pp.2699-2711. https://doi.org/10.1080/15623599.2020.1819584

Akturk, B., 2022. *Digital twin for enhanced construction project management during construction*. MSc. Istanbul Technical University.

Al-Ashmori, Y.Y., Othman, I., Rahmawati, Y., Amran, Y.H.M., Sabah, S.H.A., Rafindadi, A.D. and Mikić, M., 2020. BIM benefits and its influence on the BIM implementation in Malaysia. *Ain Shams Engineering Journal*, [e-journal] 11(4), pp.1013-19. https://doi.org/10.1016/j.asej.2020.02.002

AlRushood, M.A., Rahbar, F., Selim, S.Z. and Dweiri, F., 2023. Accelerating use of drones and robotics in post-pandemic project supply chain. *Drones*, [e-journal] 7(5), 313. https://doi.org/10.3390/drones7050313

Ameyaw, E.E., Edwards, D.J., Kumar, B., Thurairajah, N., Owusu-Manu, D.G. and Oppong, G.D., 2023. Critical factors influencing adoption of blockchain-enabled smart contracts in construction projects. *Journal of Construction Engineering and Management*, [e-journal] 149(3), 04023003. https://doi.org/10.1061/JCEMD4.COENG-12081

Aryal, A., Ghahramani, A. and Becerik-Gerber, B., 2017. Monitoring fatigue in construction workers using physiological measurements. *Automation in Construction*, [e-journal] 82, pp.154-65. https://doi.org/10.1016/j.autcon.2017.03.003

Awolusi, I., Marks, E. and Hallowell, M., 2018. Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices. *Automation in Construction*, [e-journal] 85, pp.96-106. https://doi.org/10.1016/j.autcon.2017.10.010

Bahrin, M.A.K., Othman, M.F., Azli, N.H.N. and Talib, M.F., 2016. Industry 4.0: A review on industrial automation and robotic. *Jurnal Teknologi*, [e-journal] 78(6-13), pp 137-43. https://doi.org/10.11113/jt.v78.9285

Bakchan, A., Faust, K.M. and Leite, F., 2019. Seven-dimensional automated construction waste quantification and management framework: Integration with project and site planning. *Resources, Conservation and Recycling*, [e-journal] 146, pp.462-74. https://doi.org/10.1016/j.resconrec.2019.02.020

Barlish, K. and Sullivan, K., 2012. How to measure the benefits of BIM - A case study approach. *Automation in Construction*, [e-journal] 24, pp.149-59. https://doi.org/10.1016/j.autcon.2012.02.008

Bean, T.K., Mustapa, F.D. and Mustapa, M., 2019. Unbundling transaction cost components in building information modeling adoption procurement. *International Journal of Recent Technology and Engineering*, [e-journal] 8(2 Special), pp.333-38. https://doi.org/10.35940/ijrte.B1077.0982S919

Becerik-Gerber, B., Jazizadeh, F., Li, N. and Calis, G., 2011. Application areas and data requirements for BIM-enabled facilities management. *Journal of Construction Engineering and Management*, [e-journal] 138(3), pp.431-42. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000433

Bosché, F., 2010. Automated recognition of 3D CAD model objects in laser scans and calculation of as-built dimensions for dimensional compliance control in construction. *Advanced Engineering Informatics*, [e-journal] 24(1), pp.107-18. https://doi.org/10.1016/j.aei.2009.08.006

Braun, A., Tuttas, S., Borrmann, A. and Stilla, U., 2015. A concept for automated construction progress monitoring using BIM-based geometric constraints and photogrammetric point clouds. *Journal of Information Technology in Construction*, [e-journal] 20(5), pp.68-79. http://www.itcon.org/2015/5.

Bügler, M., Borrmann, A., Ogunmakin, G., Vela, P.A. and Teizer, J., 2017. Fusion of photogrammetry and video analysis for productivity assessment of earthwork processes. *Computer-Aided Civil and Infrastructure Engineering*, [e-journal] 32(2), pp.107-23. https://doi.org/10.1111/mice.12235

Calvetti, D., Mêda, P., Gonçalves, M.C. and Sousa, H., 2020. Worker 4.0: The future of sensored construction sites. *Buildings*, [e-journal] 10(10), 169. https://doi.org/10.3390/buildings10100169

Camacho, D.D., Clayton, P., O'Brien, W.J., Seepersad, C., Juenger, M., Ferron, R. and Salamone, S., 2018. Applications of additive manufacturing in the construction industry-A forward-looking review. *Automation in Construction,* [e-journal] 89, pp.110-19. https://doi.org/10.1016/j.autcon.2017.12.031

Carbonari, A., Giretti, A. and Naticchia, B., 2011. A proactive system for real-time safety management in construction sites. *Automation in Construction*, [e-journal] 20(6), pp.686-98. https://doi.org/10.1016/j.autcon.2011.04.019

Celik, Y., Petri, I. and Rezgui, Y., 2023. Integrating BIM and blockchain across construction life-cycle and supply chains. *Computers in Industry*, [e-journal] 148, 103886. https://doi.org/10.1016/j.compind.2023.103886

Chadegani, A.A., Salehi, H., Yunus, M.M., Farhadi, H., Fooladi, M., Farhadi, M. and Ebrahim, N.A., 2013. A comparison between two main academic literature collections: Web of Science and Scopus databases. *Asian Journal of Social Science,* [e-journal] 9(5), pp.18-26.

Chalhoub, J. and Ayer, S.K., 2018. Using mixed reality for electrical construction design communication. *Automation in Construction*, [e-journal] 86, pp.1-10. https://doi.org/10.1016/j.autcon.2017.10.028

Chen, W., Chen, K., Cheng, J.C.P., Wang, Q. and Gan, V.J.L., 2018. BIM-based framework for automatic scheduling of facility maintenance work orders. *Automation in Construction*, [e-journal] 91, pp.15-30. https://doi.org/10.1016/j.autcon.2018.03.007

Chen, K., 2020. Enhancing construction safety management through edge computing: Framework and scenarios. *Journal of Information Technology in Construction*, [e-journal] 25, pp.438-51. https://doi.org/10.36680/j.itcon.2020.025

Chen, C., Gu, H., Lian, S., Zhao, Y. and Xiao, B., 2022. Investigation of edge computing in computer vision-based construction resource detection. *Buildings*, [e-journal] *12*(12), 2167. https://doi.org/10.3390/buildings12122167

Chen, T., Yabuki, N. and Fukuda, T., 2023. Motion recognition method for construction workers using selective depth inspection and optimal inertial measurement unit sensors. *Civil Engineering*, [e-journal] 4(1), pp.204-23. https://doi.org/10.3390/civileng4010013

Chen, S., Zeng, Y., Majdi, A., Salameh, A.A., Alkhalifah, T., Alturise, F. and Ali, H.E., 2023. Potential features of building information modelling for application of project management knowledge areas as advances modeling tools. *Advances in Engineering Software*, [e-journal] 176, 103372. https://doi.org/10.1016/j.advengsoft.2022.103372

UTS ePRESS

Cheng, T., Venugopal, M., Teizer, J. and Vela, P.A., 2011. Performance evaluation of ultra wideband technology for construction resource location tracking in harsh environments. *Automation in Construction*, [e-journal] 20(8), pp.1173-84. https://doi.org/10.1016/j.autcon.2011.05.001

Cheng, T., Migliaccio, G.C., Teizer, J. and Gatti, U.C., 2013a. Data fusion of real-time location sensing and physiological status monitoring for ergonomics analysis of construction workers. *Journal of Computing in Civil Engineering*, [e-journal] 27(3), pp.320-35. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000222

Cheng, T., Teizer, J., Migliaccio, G.C. and Gatti, U.C., 2013b. Automated task-level activity analysis through fusion of real time location sensors and worker's thoracic posture data. *Automation in Construction,* [e-journal] 29, pp.24-39. https://doi.org/10.1016/j.autcon.2012.08.003

Cheng, C.F., Rashidi, A., Davenport, M.A. and Anderson, D.V., 2017. Activity analysis of construction equipment using audio signals and support vector machines. *Automation in Construction*, [e-journal] 81, pp.240-53. https://doi.org/10.1016/j.autcon.2017.06.005

Choudhry, R.M., 2017. Achieving safety and productivity in construction projects. *Journal of Civil Engineering and Management*, 23(2), pp.311-18. https://doi.org/10.3846/13923730.2015.1068842

Chu, B., Jung, K., Lim, M.T. and Hong, D., 2013. Robot-based construction automation: An application to steel beam assembly (Part I). *Automation in Construction*, [e-journal] *32*, pp.46-61. https://doi.org/10.1016/j.autcon.2012.12.016

Conde, A.J.L, García-Sanz-Calcedo, J. and Rodríguez, A.M.R., 2020. Use of BIM with photogrammetry support in small construction projects. Case study for commercial franchises. *Journal of Civil Engineering and Management*, [e-journal] 26(6), pp.513-23. https://doi.org/10.3846/jcem.2020.12611

Craveiro, F., Duarte, J.P., Bartolo, H. and Bartolo, P.J., 2019. Additive manufacturing as an enabling technology for digital construction: A perspective on Construction 4.0. *Automation in Construction*, [e-journal] 103, pp.251-67. https://doi.org/10.1016/j.autcon.2019.03.011

Dakhli, Z., Lafhaj, Z. and Mossman, A., 2019. The potential of blockchain in building construction. *Buildings*, [e-journal] 9(4), 77. https://doi.org/10.3390/buildings9040077

de Soto, B.G., Agustí-Juan, I., Hunhevicz, J., Joss, S., Graser, K., Habert, G. and Adey, B.T., 2018. Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall. *Automation in Construction,* [e-journal] 92, pp.297-311. https://doi.org/10.1016/j.autcon.2018.04.004

Dilakshan, S., Rathnasinghe, A.P. and Seneviratne, L.D.I.P., 2021. Potential of internet of things (Iot) in the construction industry. *World Construction Symposium*, [e-journal] pp.445-57. https://doi.org/10.31705/WCS.2021.39

Dobrucali, E., Sadikoglu, E., Demirkesen, S., Zhang, C., Tezel, A. and Kiral, I.A., 2023. A bibliometric analysis of digital technologies use in construction health and safety. *Engineering, Construction and Architectural Management*, [e-journal]. https://doi.org/10.1108/ECAM-08-2022-0798

Dong, Z., Chen, J. and Lu, W., 2022. Computer vision to recognize construction waste compositions: A novel boundary-aware transformer (BAT) model. *Journal of Environmental Management*, [e-journal] 305, 114405. https://doi.org/10.1016/j.jenvman.2021.114405

El Asmar, P.G., Chalhoub, J., Ayer, S.K. and Abdallah, A.S., 2021. Contextualizing benefits and limitations reported for augmented reality in construction research. *Journal of Information Technology in Construction*, [e-journal] 26, pp.720-38. https://doi.org/10.36680/j.itcon.2021.039

Falagas, M.E., Pitsouni, E.I., Malietzis, G.A. and Pappas, G., 2008. Comparison of PubMed, Scopus, web of science, and Google scholar: strengths and weaknesses. *The FASEB Journal,* [e-journal] 22(2), pp.338-42. https://doi.org/10.1096/fj.07-9492LSF

Fang, W., Ding, L., Luo, H. and Love, P.E.D., 2018. Falls from heights: A computer vision-based approach for safety harness detection. *Automation in Construction*, [e-journal] 91, pp.53-61. https://doi.org/10.1016/j.autcon.2018.02.018

Fang, W., Ding, L., Love, P.E.D., Luo, H., Li, H., Peña-Mora, F., Zhong, B. and Zhou, C., 2020. Computer vision applications in construction safety assurance. *Automation in Construction*, [e-journal] 110, 103013. https://doi.org/10.1016/j.autcon.2019.103013

Fargnoli, M., Lleshaj, A., Lombardi, M., Sciarretta, N. and Di Gravio, G., 2019. A BIM-based PSS approach for the management of maintenance operations of building equipment. *Buildings*, [e-journal] 9(6), 139. https://doi.org/10.3390/buildings9060139

Fugate, H. and Alzraiee, H., 2023. Quantitative analysis of construction labor acceptance of wearable sensing devices to enhance workers' safety. *Results in Engineering*, [e-journal] 17, 100841. https://doi.org/10.1016/j.rineng.2022.100841

Golabchi, A., Han, S.U., AbouRizk, S. and Kanerva, J., 2016. Micro-motion level simulation for efficiency analysis and duration estimation of manual operations. *Automation in Construction*, [e-journal] 71, pp.443-52. https://doi.org/10.1016/j.autcon.2016.08.028

Golabchi, A., Guo, X., Liu, M., Han, S., Lee, S. and AbouRizk, S., 2018. An integrated ergonomics framework for evaluation and design of construction operations. *Automation in Construction*, [e-journal] 95, pp. 72-85. https://doi.org/10.1016/j.autcon.2018.08.003

Golparvar-Fard, M., Peña-Mora, F., Arboleda, C.A. and Lee, S., 2009. Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs. *Journal of Computing in Civil Engineering*, [e-journal] *23*(6), pp.391-404. https://doi.org/10.1061/(ASCE)0887-3801(2009)23:6(391)

Golparvar-Fard, M., Heydarian, A. and Niebles, J.C., 2013. Vision-based action recognition of earthmoving equipment using spatio-temporal features and support vector machine classifiers. *Advanced Engineering Informatics,* [e-journal] 27(4), pp.652-63. https://doi.org/10.1016/j.aei.2013.09.001

Gong, Y., Yang, K., Seo, J.O. and Lee, J.G., 2022. Wearable acceleration-based action recognition for long-term and continuous activity analysis in construction site. *Journal of Building Engineering*, [e-journal] 52, 104448. https://doi.org/10.1016/j.jobe.2022.104448

Gonsalves, N.J., Ogunseiju, O.R., Akanmu, A.A. and Nnaji, C.A., 2021. Assessment of a passive wearable robot for reducing low back disorders during rebar work. *Journal of Information Technology in Construction*, [e-journal] 26, pp.936-52. https://doi.org/10.36680/j.itcon.2021.050

Guo, J., Yuan, L. and Wang, Q., 2020. Time and cost analysis of geometric quality assessment of structural columns based on 3D terrestrial laser scanning. *Automation in Construction*, [e-journal] 110, 103014. https://doi.org/10.1016/j.autcon.2019.103014

Gupta, P. and Jha, K.N., 2023. A decentralized and automated contracting system using a blockchain-enabled network of stakeholders in construction megaprojects. *Journal of Management in Engineering*, [e-journal] 39(4), 04023021. https://doi.org/10.1061/JMENEA.MEENG-5366

Gurgun, A.P., Genc, M.I., Koc, K. and Arditi, D., 2022. Exploring the barriers against using cryptocurrencies in managing construction supply chain processes. *Buildings*, [e-journal] 12(3), 357. https://doi.org/10.3390/buildings12030357

Hallowell, M.R., Teizer, J. and Blaney, W., 2010. Application of sensing technology to safety management. *Construction Research Congress 2010: Innovation for Reshaping Construction Practice*, [e-journal] pp.31-40. https://doi.org/10.1061/41109(373)4

Han, T., Ma, T., Fang, Z., Zhang, Y. and Han, C., 2022. A BIM-IoT and intelligent compaction integrated framework for advanced road compaction quality monitoring and management. *Computers and Electrical Engineering*, [e-journal] 100, 107981. https://doi.org/10.1016/j.compeleceng.2022.107981

Hire, S., Sandbhor, S., Ruikar, K. and Amarnath, C.B., 2021. BIM usage benefits and challenges for site safety application in Indian construction sector. *Asian Journal of Civil Engineering*, [e-journal] 22(7), pp.1249-67. https://doi.org/10.1007/s42107-021-00379-8

Hong, Y., Xie, H., Agapaki, E. and Brilakis, I., 2023. Graph-based automated construction scheduling without the use of BIM. *Journal of Construction Engineering and Management*, [e-journal] 149(2), 05022020. https://doi.org/10.1061/JCEMD4.COENG-12687

Honic, M., Kovacic, I., Sibenik, G. and Rechberger, H., 2019. Data- and stakeholder management framework for the implementation of BIM-based material passports. *Journal of Building Engineering*, [e-journal] 23, pp.341-50. https://doi.org/10.1016/j.jobe.2019.01.017

Hosny, S., Ibrahim, A.H. and Nabil, Y., 2023. Reducing reinforced concrete materials waste in construction projects using building information modeling in Egypt. *Journal of Information Technology in Construction*, [e-journal] 28, pp.332-45. https://doi.org/10.36680/j.itcon.2023.017

Hu, X., 2022. Application of GPS measurement technology and computer technology in visual construction simulation of construction engineering. *Mobile Information Systems*. [e-journal]. https://doi.org/10.1155/2022/8374901

Hwang, S., Seo, J.O., Jebelli, H. and Lee, S.H., 2016. Feasibility analysis of heart rate monitoring of construction workers using a photoplethysmography (PPG) sensor embedded in a wristband-type activity tracker. *Automation in Construction*, [e-journal] 71, pp.372-81. https://doi.org/10.1016/j.autcon.2016.08.029

Hwang, S. and Lee, S.H., 2017. Wristband-type wearable health devices to measure construction workers' physical demands. *Automation in Construction*, [e-journal] *83*, pp.330-40. https://doi.org/10.1016/j.autcon.2017.06.003

Ibrahim, R., Harby, A.A., Nashwan, M.S. and Elhakeem, A., 2022. Financial contract administration in construction via cryptocurrency blockchain and smart contract: A proof of concept. *Buildings*, [e-journal] 12(8), 1072. https://doi.org/10.3390/buildings12081072

Ismail, S.A., Bandi, S. and Maaz, Z.N., 2018. An appraisal into the potential application of big data in the construction industry. *International Journal of Built Environment and Sustainability*, [e-journal] 5(2). https://doi.org/10.11113/ijbes.v5.n2.274

Jacobsen, E.L. and Teizer, J., 2022. Deep learning in construction: review of applications and potential avenues. *Journal of Computing in Civil Engineering*, [e-journal] 36(2), 03121001. https://doi.org/10.1061/(ASCE)CP.1943-5487.0001010

Jang, Y., Kim, K., Leite, F., Ayer, S. and Cho, Y.K., 2021. Identifying the perception differences of emerging construction-related technologies between industry and academia to enable high levels of collaboration. *Journal of Construction Engineering and Management,* [e-journal] 147(10), 06021004. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002156

Jiang, Y., Liu, X., Kang, K., Wang, Z., Zhong, R.Y. and Huang, G.Q., 2021. Blockchain-enabled cyber-physical smart modular integrated construction. *Computers in Industry*, [e-journal] 133, 103553. https://doi.org/10.1016/j.compind.2021.103553

Jiang, Z., Messner, J.I. and Matts, E., 2023. Computer vision applications in construction and asset management phases: A literature review. *Journal of Information Technology in Construction,* [e-journal] 28, pp.176-99. https://doi.org/10.36680/j.itcon.2023.009

Jin, J., Zhang, W., Li, F., Li, M., Shi, Y., Guo, Z. and Huang, Q., 2021. Robotic binding of rebar based on active perception and planning. *Automation in Construction*, [e-journal] 132, 103939. https://doi.org/10.1016/j.autcon.2021.103939

John, S.T., Sarkar, P. and Davis, R., 2022. Energy-efficient long range wide area network for construction industry applications. *Automation in Construction*, [e-journal] 136, 104150. https://doi.org/10.1016/j.autcon.2022.104150

John, S.T., Philip, M.S., Agarwal, S., Sarkar, P. and Davis, R., 2023. IoT-enabled real-time monitoring system for plastic shrinkage of concrete. *Journal of Infrastructure Systems*, [e-journal] 29(3), 06023001. https://doi.org/10.1061/JITSE4.ISENG-2022

Jung, K., Chu, B. and Hong, D., 2013. Robot-based construction automation: An application to steel beam assembly (Part II). *Automation in Construction*, [e-journal] 32, pp.62-79. https://doi.org/10.1016/j.autcon.2012.12.011

Kang, H., Sung, S., Hong, J., Jung, S., Hong, T., Park, H.S. and Lee, D.E., 2021. Development of a real-time automated monitoring system for managing the hazardous environmental pollutants at the construction site. *Journal of Hazardous Materials*, [e-journal] 402, 123483. https://doi.org/10.1016/j.jhazmat.2020.123483

Karmakar, A., Singh, A.R. and Kumar, V.S., 2022. Automated route planning for construction site utilizing building information modeling. *Journal of Information Technology in Construction*, [e-journal] 27, pp.827-44. https://doi.org/10.36680/j.itcon.2022.040

Kasperzyk, C., Kim, M.K. and Brilakis, I., 2017. Automated re-prefabrication system for buildings using robotics. *Automation in Construction*, [e-journal] 83, pp.184-95. https://doi.org/10.1016/j.autcon.2017.08.002

Katiyar, A. and Kumar, P., 2022. Automated construction progress monitoring of prefabricated concrete structures using building information modeling and internet of things. *International Journal on Recent and Innovation Trends in Computing and Communication*, [e-journal] 10(7), pp.14-18. https://doi.org/10.17762/ijritcc.v10i7.5560

Khodabakhshian, A. and Toosi, H., 2021. Residential real estate valuation framework based on life cycle cost by building information modeling. *Journal of Architectural Engineering*, [e-journal] 27(3), 04021020. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000479

Kim, K., Cho, Y. and Zhang, S., 2016. Integrating work sequences and temporary structures into safety planning: Automated scaffolding-related safety hazard identification and prevention in BIM. *Automation in Construction*, [e-journal] 70, pp.128-42. https://doi.org/10.1016/j.autcon.2016.06.012

Kim, H., Lee, H.S., Park, M., Chung, B. and Hwang, S., 2016. Automated hazardous area identification using laborers' actual and optimal routes. *Automation in Construction*, [e-journal] 65, pp.21-32. https://doi.org/10.1016/j.autcon.2016.01.006

Kim, J., Golabchi, A., Han, S. and Lee, D.E., 2021. Manual operation simulation using motion-time analysis toward labor productivity estimation: A case study of concrete pouring operations. *Automation in Construction*, [e-journal] 126, 103669. https://doi.org/10.1016/j.autcon.2021.103669

Kim, S., Kim, H., Lee, J., Hong, T. and Jeong, K., 2023. An integrated assessment framework of economic, environmental, and human health impacts using scan-to-BIM and life-cycle assessment in existing buildings. *Journal of Management in Engineering*, [e-journal] 39(5), 04023034. https://doi.org/10.1061/JMENEA.MEENG-5600

Kisel, T., 2021. Cost efficiency of building information modeling use at the stage of real estate object maintenance. *International Journal of Technology*, [e-journal] 12(7), pp.1468-78. https://doi.org/10.14716/ijtech.v12i7.5382

Kruachottikul, P., Cooharojananone, N., Phanomchoeng, G., Chavarnakul, T., Kovitanggoon, K. and Trakulwaranont, D., 2021. Deep learning-based visual defect-inspection system for reinforced concrete bridge substructure: a case of Thailand's department of highways. *Journal of Civil Structural Health Monitoring*, [e-journal] 11(4), pp.949-65. https://doi.org/10.1007/s13349-021-00490-z

Kumar, V.P., Balasubramanian, M., and Raj, S.J., 2016. Robotics in construction industry. *Indian Journal of Science and Technology*, [e-journal] 9(23), pp.1-12. https://doi.org/10.17485/ijst/2016/v9i23/95974

Lee, H.S., Lee, K.P., Park, M., Baek, Y. and Lee, S., 2012. RFID-based real-time locating system for construction safety management. *Journal of Computing in Civil Engineering*, [e-journal] 26(3), pp.366-77. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000144

Lee, K.P., Lee, H.S., Park, M., Kim, H. and Han, S., 2014. A real-time location-based construction labor safety management system. *Journal of Civil Engineering and Management*, [e-journal] 20(5), pp.724-36. https://doi.org/10.3846/13923730.2013.802728

Lee, W., Lin, K.Y., Seto, E. and Migliaccio, G.C., 2017a. Wearable sensors for monitoring on-duty and off-duty worker physiological status and activities in construction. *Automation in Construction*, [e-journal] 83, pp.341-53. https://doi.org/10.1016/j.autcon.2017.06.012

Lee, M., Lee, S., Kwon, S. and Chin, S., 2017b. A study on scan data matching for reverse engineering of pipes in plant construction. *KSCE Journal of Civil Engineering*, [e-journal] 21(6), pp.2027-36. https://doi.org/10.1007/s12205-016-0929-z

Lee, Y.C., Shariatfar, M., Rashidi, A. and Lee, H.W., 2020. Evidence-driven sound detection for prenotification and identification of construction safety hazards and accidents. *Automation in Construction*, [e-journal] 113, 103127. https://doi.org/10.1016/j.autcon.2020.103127

Leng, Y., Shi, X., Hiroatsu, F., Kalachev, A. and Wan, D., 2023. Automated construction for human-robot interaction in wooden buildings: Integrated robotic construction and digital design of iSMART wooden arches. *Journal of Field Robotics*, [e-journal] 40(4), pp.810-27. https://doi.org/10.1002/rob.22154

Li, J., Greenwood, D. and Kassem, M., 2019. Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Automation in Construction,* [e-journal] 102, pp.288-307. https://doi.org/10.1016/j.autcon.2019.02.005

Li, K., Luo, H. and Skibniewski, M.J., 2019. A non-centralized adaptive method for dynamic planning of construction components storage areas. *Advanced Engineering Informatics*, [e-journal] 39, pp.80-94. https://doi.org/10.1016/j.aei.2018.12.001

Lin, Z.H., Chen, A.Y. and Hsieh, S.H., 2021. Temporal image analytics for abnormal construction activity identification. *Automation in Construction*, [e-journal] 124, 103572. https://doi.org/10.1016/j.autcon.2021.103572

Liu, S., Meng, X. and Tam, C., 2015. Building information modeling based building design optimization for sustainability. *Energy and Buildings,* [e-journal] 105, pp.139-53. https://doi.org/10.1016/j.enbuild.2015.06.037

Liu, F. and Seipel, S., 2018. Precision study on augmented reality-based visual guidance for facility management tasks. *Automation in Construction*, [e-journal] 90, pp.79-90. https://doi.org/10.1016/j.autcon.2018.02.020

Liu, C., AbouRizk, S., Morley, D. and Lei, Z., 2020. Data-driven simulation-based analytics for heavy equipment life-cycle cost. *Journal of Construction Engineering and Management*, [e-journal] 146(5), 04020038. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001816

Lu, Y., Li, Y., Skibniewski, M., Wu, Z., Wang, R. and Le, Y., 2015. Information and communication technology applications in architecture, engineering, and construction organisations: A 15-year review. *Journal of Management in Engineering*, [e-journal] 31(1), A4014010. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000319

Lu, Q. and Lee, S., 2017. Image-based technologies for constructing as-is building information models for existing buildings. *Journal of Computing in Civil Engineering*, [e-journal] 31(4), 04017005. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000652

Lu, W., Wu, L. and Zhao, R., 2023. Rebuilding trust in the construction industry: a blockchain-based deployment framework. *International Journal of Construction Management*, [e-journal] 23(8), pp.1405-16. https://doi.org/10.1080/15623599.2021.1974683

Ma, G., Wu, M., Wu, Z. and Yang, W., 2021. Single-shot multibox detector- and building information modeling-based quality inspection model for construction projects. *Journal of Building Engineering*, [e-journal] 38, 102216. https://doi.org/10.1016/j.jobe.2021.102216

Magill, L.J., Jafarifar, N., Watson, A. and Omotayo, T., 2022. 4D BIM integrated construction supply chain logistics to optimise on-site production. *International Journal of Construction Management*, [e-journal] 22(12), pp.2325-34. https://doi.org/10.1080/15623599.2020.1786623

Mahmoudi, A., Sadeghi, M. and Naeni, L.M., 2023. Blockchain and supply chain finance for sustainable construction industry: ensemble ranking using ordinal priority approach. *Operations Management Research*, [e-journal]. https://doi.org/10.1007/s12063-023-00374-z

Martins, S.S., Evangelista, A.C.J., Hammad, A.W.A., Tam, V.W.Y. and Haddad, A., 2022. Evaluation of 4D BIM tools applicability in construction planning efficiency. *International Journal of Construction Management*, [e-journal] 22(15), pp.2987-3000. https://doi.org/10.1080/15623599.2020.1837718

Mechtcherine, V., Nerella, V.N., Will, F., Näther, M., Otto, J. and Krause, M., 2019. Large-scale digital concrete construction-CONPrint3D concept for on-site, monolithic 3D-printing. *Automation in Construction,* [e-journal] 107, 102933. https://doi.org/10.1016/j.autcon.2019.102933

Melenbrink, N., Werfel, J. and Menges, A., 2020. On-site autonomous construction robots: Towards unsupervised building. *Automation in Construction*, [e-journal] 119, 103312. https://doi.org/10.1016/j.autcon.2020.103312

Mesároš, P., Mandičák, T. and Behúnová, A., 2022. Use of BIM technology and impact on productivity in construction project management. *Wireless Networks*, [e-journal] 28(2), pp.855-62. https://doi.org/10.1007/s11276-020-02302-6

Mo, Y., Zhao, D., Du, J., Syal, M., Aziz, A. and Li, H., 2020. Automated staff assignment for building maintenance using natural language processing. *Automation in Construction*, [e-journal] 113, 103150. https://doi.org/10.1016/j.autcon.2020.103150

Moon, H., Dawood, N. and Kang, L., 2014. Development of workspace conflict visualization system using 4D object of work schedule. *Advanced Engineering Informatics*, [e-journal] 28(1), pp.50-65. https://doi.org/10.1016/j.aei.2013.12.001

Moon, D., Chung, S., Kwon, S., Seo, J. and Shin, J., 2019. Comparison and utilization of point cloud generated from photogrammetry and laser scanning: 3D world model for smart heavy equipment planning. *Automation in Construction*, [e-journal] 98, pp.322-31. https://doi.org/10.1016/j.autcon.2018.07.020

Motayyeb, S., Samadzedegan, F., Dadrass Javan, F. and Hosseinpour, H., 2023. Fusion of UAV-based infrared and visible images for thermal leakage map generation of building facades. *Heliyon*, [e-journal] 9(3). https://doi.org/10.1016/j.heliyon.2023.e14551

Nabavi, A., Ramaji, I., Sadeghi, N. and Anderson, A., 2023. Leveraging natural language processing for automated information inquiry from building information models. *Journal of Information Technology in Construction*, [e-journal] 28, pp.266-85. https://doi.org/10.36680/j.itcon.2023.013

Najafi, F.T. and Fu, X., 2017. Economic evaluation of robots in construction. *9th ISARC International Symposium on Automation and Robotics in Construction*, [e-journal] pp.201-07. https://doi.org/10.22260/ISARC1992/0027

Nical, A.K. and Wodyński, W., 2016. Enhancing facility management through BIM 6D. *Procedia Engineering*, [e-journal] 164, pp.299-306. https://doi.org/10.1016/j.proeng.2016.11.623

UTS ePRESS

Oh, J.K., Jang, G., Oh, S., Lee, J.H., Yi, B.J., Moon, Y.S., Lee, J.S. and Choi, Y., 2009. Bridge inspection robot system with machine vision. *Automation in Construction*, [e-journal] 18(7), pp.929-41. https://doi.org/10.1016/j.autcon.2009.04.003

Ojha, A., Habibnezhad, M., Jebelli, H. and Leicht, R., 2022. Barrier analysis of effective implementation of robotics in the construction industry. *Construction Research Congress 2022: Computer Applications, Automation, and Data Analytics*, [e-journal] pp.661-69. https://doi.org/10.1061/9780784483961.069

Oke, A.E., Aliu, J., Oluwasefunmi Fadamiro, P., Akanni, P.O. and Stephen, S.S., 2023a. Attaining digital transformation in construction: An appraisal of the awareness and usage of automation techniques. *Journal of Building Engineering*, [e-journal] 67, 105968. https://doi.org/10.1016/j.jobe.2023.105968

Oke, A.E., Aliu, J., Jamir Singh, P.S., Onajite, S.A., Shaharudin Samsurijan, M. and Azura Ramli, R., 2023b. Appraisal of awareness and usage of digital technologies for sustainable well-being among construction workers in a developing economy. *International Journal of Construction Management*, [e-journal]. https://doi.org/10.1080/15623599.2023.2179628

Okpala, I., Nnaji, C. and Karakhan, A.A., 2020. Utilizing emerging technologies for construction safety risk mitigation. *Practice Periodical on Structural Design and Construction*, [e-journal] 25(2), 04020002. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000468

Omar, H., Mahdjoubi, L. and Kheder, G., 2018. Towards an automated photogrammetry-based approach for monitoring and controlling construction site activities. *Computers in Industry*, [e-journal] 98, pp.172-82. https://doi.org/10.1016/j.compind.2018.03.012

Opoku, D.G.J., Perera, S., Osei-Kyei, R. and Rashidi, M., 2021. Digital twin application in the construction industry: A literature review. *Journal of Building Engineering,* [e-journal] 40, 102726. https://doi.org/10.1016/j.jobe.2021.102726

Ozturk, G.B., 2021. Digital twin research in the AECO-FM industry. *Journal of Building Engineering*, [e-journal] 40, 102730. https://doi.org/10.1016/j.jobe.2021.102730

Pakhale, P.D. and Pal, A., 2020. Digital project management in infrastructure project: a case study of Nagpur Metro Rail Project. *Asian Journal of Civil Engineering*, [e-journal] 21(4), pp.639-47. https://doi.org/10.1007/s42107-020-00224-4

Park, J. and Cai, H., 2017. WBS-based dynamic multi-dimensional BIM database for total construction as-built documentation. *Automation in Construction*, [e-journal] 77, pp.15-23. https://doi.org/10.1016/j.autcon.2017.01.021

Peng, Z., Kong, Q., Yuan, C., Li, R. and Chi, H.L., 2023. Development of acoustic denoising learning network for communication enhancement in construction sites. *Advanced Engineering Informatics*, [e-journal] 56, 101981. https://doi.org/10.1016/j.aei.2023.101981

Porwal, A. and Hewage, K. N., 2013. Building Information Modeling (BIM) partnering framework for public construction projects. *Automation in Construction,* [e-journal] 31, pp.204-14. https://doi.org/10.1016/j.autcon.2012.12.004

Rahimian, A., Hosseini, M.R., Martek, I., Taroun, A., Alvanchi, A. and Odeh, I., 2022. Predicting communication quality in construction projects: A fully-connected deep neural network approach. *Automation in Construction*, [e-journal] 139, 104268. https://doi.org/10.1016/j.autcon.2022.104268

Ratajczak, J., Riedl, M. and Matt, D.T., 2019. BIM-based and AR application combined with location-based management system for the improvement of the construction performance. *Buildings*, [e-journal] 9(5), 118. https://doi.org/10.3390/buildings9050118

Reichenbach, S. and Kromoser, B., 2021. State of practice of automation in precast concrete production. *Journal of Building Engineering*, [e-journal] 43, 102527. https://doi.org/10.1016/j.jobe.2021.102527

UTS ePRESS

Rodrigo, N., Omrany, H., Chang, R. and Zuo, J., 2023. Leveraging digital technologies for circular economy in construction industry: a way forward. *Smart and Sustainable Built Environment*, [e-journal]. https://doi.org/10.1108/SASBE-05-2023-0111

Rodrigues, F., Baptista, J.S. and Pinto, D., 2022. BIM approach in construction safety-a case study on preventing falls from height. *Buildings*, [e-journal] 12(1), 73. https://doi.org/10.3390/buildings12010073

Rui, Y., Yaik-Wah, L. and Siang, T.C., 2021. Construction project management based on building information modeling (BIM). *Civil Engineering and Architecture*, [e-journal] 9(6), pp.2055-61. https://doi.org/10.13189/cea.2021.090633

Ryu, J., Seo, J., Jebelli, H. and Lee, S., 2019. Automated action recognition using an accelerometer-embedded wristband-type activity tracker. *Journal of Construction Engineering and Management*, [e-journal] 145(1), 04018114. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001579

Sabillon, C., Rashidi, A., Samanta, B., Davenport, M.A. and Anderson, D.V., 2020. Audio-based bayesian model for productivity estimation of cyclic construction activities. *Journal of Computing in Civil Engineering*, [e-journal] 34(1), 04019048. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000863

Sangchul, K. and Tae-Hwa, J., 2016. An application of PDA in building construction project for enhancing productivity. *Indian Journal of Science and Technology*, [e-journal] 9(41). https://doi.org/10.17485/ijst/2016/v9i41/103953

Sanhudo, L., Calvetti, D., Martins, J. P., Ramos, N.M.M., Mêda, P., Gonçalves, M.C. and Sousa, H., 2021. Activity classification using accelerometers and machine learning for complex construction worker activities. *Journal of Building Engineering*, [e-journal] 35, 102001. https://doi.org/10.1016/j.jobe.2020.102001

Santos, R., Costa, A.A. and Grilo, A., 2017. Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015. *Automation in Construction,* [e-journal] 80, pp.118-36. https://doi.org/10.1016/j.autcon.2017.03.005

Santos, R., Costa, A.A., Silvestre, J.D. and Pyl, L., 2019. Integration of LCA and LCC analysis within a BIM-based environment. *Automation in Construction,* [e-journal] 103, pp.127-49. https://doi.org/10.1016/j.autcon.2019.02.011

Satyanarayanan, M., 2017. The emergence of edge computing. *Computer*, [e-journal] 50(1), pp.30-39. https://doi.org/10.1109/MC.2017.9

Sepasgozar, S.M.E., 2021. Differentiating digital twin from digital shadow: Elucidating a paradigm shift to expedite a smart, sustainable built environment. *Buildings*, [e-journal] 11(4), 151. https://doi.org/10.3390/buildings11040151

Shahzad, M., Shafiq, M.T., Douglas, D. and Kassem, M., 2022. Digital twins in built environments: An investigation of the characteristics, applications, and challenges. *Buildings*, [e-journal] 12(2), 120. https://doi.org/10.3390/buildings12020120

Singh, A., Dwivedi, A., Agrawal, D. and Singh, D., 2023. Identifying issues in adoption of AI practices in construction supply chains: towards managing sustainability. *Operations Management Research,* [e-journal]. https://doi.org/10.1007/s12063-022-00344-x

Skibniewski, M.J., 1988. Framework for decision making on implementing robotics in construction. *Journal of Computing in Civil Engineering*, [e-journal] 2(2), pp.188-201. https://doi.org/10.1061/(ASCE)0887-3801(1988)2:2(188)

Slaton, T., Hernandez, C. and Akhavian, R., 2020. Construction activity recognition with convolutional recurrent networks. *Automation in Construction*, [e-journal] 113, 103138. https://doi.org/10.1016/j.autcon.2020.103138

Son, H., Seong, H., Choi, H. and Kim, C., 2019. Real-time vision-based warning system for prevention of collisions between workers and heavy equipment. *Journal of Computing in Civil Engineering*, [e-journal] 33(5), 04019029. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000845

Stanley, R. and Thurnell, D., 2014. The benefits of, and barriers to, implementation of 5D BIM for quantity surveying in New Zealand. *Australasian Journal of Construction Economics and Building*, [e-journal] 14(1), pp.105-17. https://doi.org/10.5130/AJCEB.v14i1.3786

Tang, X., Wang, M., Wang, Q., Guo, J. and Zhang, J., 2022. Benefits of terrestrial laser scanning for construction QA/QC: A time and cost analysis. *Journal of Management in Engineering*, [e-journal] 38(2), 05022001. https://doi.org/10.1061/(ASCE)ME.1943-5479.0001012

Tao, G., Feng, H., Feng, J. and Wang, T., 2022. Dynamic multi-objective construction site layout planning based on BIM. *KSCE Journal of Civil Engineering*, [e-journal] 26(4), pp.1522-34. https://doi.org/10.1007/s12205-022-0708-y

Tariq, A., Ali, B., Ullah, F. and Alqahtani, F.K., 2023. Reducing falls from heights through BIM: A dedicated system for visualizing safety standards. *Buildings*, [e-journal] 13(3), 671. https://doi.org/10.3390/buildings13030671

Tavares, P., Costa, C.M., Rocha, L., Malaca, P., Costa, P., Moreira, A.P., Sousa, A. and Veiga, G., 2019. Collaborative welding system using BIM for robotic reprogramming and spatial augmented reality. *Automation in Construction*, [e-journal] 106, 102825. https://doi.org/10.1016/j.autcon.2019.04.020

Tehrani, B.M., BuHamdan, S. and Alwisy, A., 2022. Robotics in assembly-based industrialized construction: a narrative review and a look forward. *International Journal of Intelligent Robotics and Applications*, [e-journal]. https://doi.org/10.1007/s41315-022-00257-9

Tian, Z., Yu, Y., Xu, F. and Zhang, Z., 2023. Dynamic hazardous proximity zone design for excavator based on 3D mechanical arm pose estimation via computer vision. *Journal of Construction Engineering and Management*, [e-journal] 149(7), 04023048. https://doi.org/10.1061/JCEMD4.COENG-13071

Tuttas, S., Braun, A., Borrmann, A. and Stilla, U., 2015. Validation of BIM components by photogrammetric point clouds for construction site monitoring. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, [e-journal] 2, pp.231-37. https://doi.org/10.5194/isprsannals-II-3-W4-231-2015

Valero, E., Sivanathan, A., Bosché, F. and Abdel-Wahab, M., 2016. Musculoskeletal disorders in construction: A review and a novel system for activity tracking with body area network. *Applied Ergonomics*, [e-journal] 54, pp.120-30. https://doi.org/10.1016/j.apergo.2015.11.020

Veerendra, G.T.N., Dey, S., Manoj, A.V.P. and Kumaravel, B., 2022. Life cycle assessment for a suburban building located within the vicinity using Revit Architecture. *Journal of Building Pathology and Rehabilitation*, [e-journal] 7(1), 56. https://doi.org/10.1007/s41024-022-00199-6

Vinod, S., Shakor, P., Sartipi, F. and Karakouzian, M., 2022. Object detection using ESP32 cameras for quality control of steel components in manufacturing structures. *Arabian Journal for Science and Engineering*, [e-journal]. https://doi.org/10.1007/s13369-022-07562-2

Wang, Z., Hu, H. and Zhou, W., 2017. RFID enabled knowledge-based precast construction supply chain. *Computer-Aided Civil and Infrastructure Engineering*, [e-journal] 32(6), pp.499-514. https://doi.org/10.1111/mice.12254

Wang, D., Fan, J., Fu, H. and Zhang, B., 2018. Research on optimization of big data construction engineering quality management based on RnN-LSTM. *Complexity,* [e-journal]. https://doi.org/10.1155/2018/9691868

Wang, Z. and Rezazadeh Azar, E., 2019. BIM-based draft schedule generation in reinforced concrete-framed buildings. *Construction Innovation*, [e-journal] 19(2), pp.280-94.

Wang, J., Cheng, R., Liu, M. and Liao, P. C., 2021. Research trends of human-computer interaction studies in construction hazard recognition: A bibliometric review. *Sensors,* [e-journal] 21(18), 6172. https://doi.org/10.3390/s21186172

Wang, Y., 2021. BIM + VR technology in construction management of construction engineering. *Journal of Physics: Conference Series*, [e-journal] 2037(1). https://doi.org/10.1088/1742-6596/2037/1/012083

Wang, D., Wang, X., Ren, B., Wang, J., Zeng, T., Kang, D. and Wang, G., 2022. Vision-based productivity analysis of cable crane transportation using augmented reality-based synthetic image. *Journal of Computing in Civil Engineering*, [e-journal] 36(1), 04021030. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000994

Wu, H., Li, H., Chi, H.L., Peng, Z., Chang, S. and Wu, Y., 2023. Thermal image-based hand gesture recognition for worker-robot collaboration in the construction industry: A feasible study. *Advanced Engineering Informatics*, [e-journal] 56, 101939. https://doi.org/10.1016/j.aei.2023.101939

Xiao, B. and Zhu, Z., 2018. Two-dimensional visual tracking in construction scenarios: A comparative study. *Journal of Computing in Civil Engineering*, [e-journal] 32(3), 04018006. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000738

Xiao, B. and Kang, S.C., 2020. Vision-based method integrating deep learning detection for tracking multiple construction machines. *Journal of Computing in Civil Engineering*, [e-journal] 35(2), 04020071. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000957

Xiao, B. and Kang, S.C., 2021. Development of an image data set of construction machines for deep learning object detection. *Journal of Computing in Civil Engineering*, [e-journal] 35(2), 05020005. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000945

Xiao, B., Zhang, Y., Chen, Y. and Yin, X., 2021. A semi-supervised learning detection method for vision-based monitoring of construction sites by integrating teacher-student networks and data augmentation. *Advanced Engineering Informatics*, [e-journal] 50, 101372. https://doi.org/10.1016/j.aei.2021.101372

Xie, H. and Yang, Z., 2021. The risk management mode of construction project management in the multimedia environment of internet of things. *Mobile Information Systems*, [e-journal]. https://doi.org/10.1155/2021/1311474

Yan, X., Li, H., Zhang, H. and Rose, T.M., 2018. Personalized method for self-management of trunk postural ergonomic hazards in construction rebar ironwork. *Advanced Engineering Informatics*, [e-journal] 37, pp.31-41. https://doi.org/10.1016/j.aei.2018.04.013

Yang, R.J., Gunarathna, C.L., McDermott, V., Lingard, H., Zhao, H. and Liu, C., 2020a. Opportunities for improving construction health and safety using real-time H&S management innovations: A socio-technical-economic perspective. *International Journal of Construction Management*, [e-journal] 20(5), pp.534-54. https://doi.org/10.1080/15623599.2018.1490866

Yang, X., Yu, Y., Shirowzhan, S., Sepasgozer, S. and Li, H., 2020b. Automated PPE-tool pair check system for construction safety using smart IoT. *Journal of Building Engineering*, [e-journal] 32, 101721. https://doi.org/10.1016/j.jobe.2020.101721

Yang, R., Wakefield, R., Lyu, S., Jayasuriya, S., Han, F., Yi, X., Yang, X., Amarasinghe, G. and Chen, S., 2020c. Public and private blockchain in construction business process and information integration. *Automation in Construction*, [e-journal] 118, 103276. https://doi.org/10.1016/j.autcon.2020.103276

Ye, X., Zeng, N. and König, M., 2022. Systematic literature review on smart contracts in the construction industry: Potentials, benefits, and challenges. *Frontiers of engineering management*, [e-journal] 9(2), pp.196-213. https://doi.org/10.1007/s42524-022-0188-2

Yen, K.S., Lasky, T.A. and Ravani, B., 2014. Cost-benefit analysis of mobile terrestrial laser scanning applications for highway infrastructure. *Journal of Infrastructure Systems*, [e-journal] 20(4), 04014022. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000192

You, Z. and Wu, C., 2019. A framework for data-driven informatization of the construction company. *Advanced Engineering Informatics*, [e-journal] 39, pp.269-77. https://doi.org/10.1016/j.aei.2019.02.002

Yu, Y., Li, H., Umer, W., Dong, C., Yang, X., Skitmore, M. and Wong, A.Y.L., 2019a. Automatic biomechanical workload estimation for construction workers by computer vision and smart insoles. *Journal of Computing in Civil Engineering*, [e-journal] 33(3), 04019010. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000827

Yu, Y., Yang, X., Li, H., Luo, X., Guo, H. and Fang, Q., 2019b. Joint-level vision-based ergonomic assessment tool for construction workers. *Journal of Construction Engineering and Management*, [e-journal] 145(5), 04019025. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001647

Zhang, C. and Arditi, D., 2013. Automated progress control using laser scanning technology. *Automation in Construction*, [e-journal] 36, pp.108-16. https://doi.org/10.1016/j.autcon.2013.08.012

Zhang, Y., 2021. Safety management of civil engineering construction based on artificial intelligence and machine vision technology. *Advances in Civil Engineering,* [e-journal]. https://doi.org/10.1155/2021/3769634

Zhong, B., Xing, X., Love, P., Wang, X. and Luo, H., 2019. Convolutional neural network: Deep learning-based classification of building quality problems. *Advanced Engineering Informatics*, [e-journal] 40, pp.46-57. https://doi.org/10.1016/j.aei.2019.02.009

Zhou, Z., 2022. An intelligent bridge management and maintenance model using BIM technology. *Mobile Information Systems*, [e-journal]. https://doi.org/10.1155/2022/7130546

Zhu, Z., Dutta, A. and Dai, F., 2021. Exoskeletons for manual material handling - A review and implication for construction applications. *Automation in Construction*, [e-journal] 122, 103493. https://doi.org/10.1016/j.autcon.2020.103493