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Automation in architecture, engineering and construction: a scientometric analysis and implications for management

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Abstract

Purpose – Many economic, political and socio-cultural events in the 2020s have been strong headwinds for architecture, engineering and construction (AEC). Nevertheless, technological advancements (e.g. artificial intelligence (AI), big data and robotics) provide promising avenues for the development of AEC. This study aims to map the state of the literature on automation in AEC and thereby be of value not only to those researching automation and its composition of a variety of distinct technological and system classes within AEC, but also to practitioners and policymakers in shaping the future of AEC.

Design/methodology/approach – This review adopts scientometric methods, which have been effective in the research of large intra and interdisciplinary domains in the past decades. The full dataset consists of 1,871 articles on automation in AEC.

Findings – This overarching scientometric review offers three interdisciplinary streams of research: technological frontiers, project monitoring and applied research in AEC. To support the scientometric analysis, the authors offer a critical integrative review of the literature to proffer a multilevel, multistage framework of automation in AEC, which demonstrates an abundance of technological paradigm discussions and the inherent need for a holistic managerial approach to automation in AEC.

Originality/value – The authors underline employee well-being, business sustainability and social growth outcomes of automation and provide several managerial implications, such as the strategic management approach, ethical management view and human resource management perspective. In doing so, the authors seek to respond to the Sustainable Development Goals proposed by the United Nations as this becomes more prevalent for the industry and all levels of society in general.

Keywords Automation, Artificial intelligence, Systematic literature review, Construction engineering and management, Scientometrics, Bibliometrics, Managerial implications

Paper type Literature review

1. Introduction

Automation is broadly referred to as the utilization of technologies to minimize human input. It allows for the replacement of labor by technology, thereby increasing efficiencies and decreasing reliance on manual labor. Automation reaches beyond artificial intelligence (AI) underpinned by algorithms (Muro *et al.*, 2019) to include systems and processes that monitor, enhance, control, and manage effective and efficient performances across industrial processes including architecture, engineering and construction (AEC).

Technological development calls for a holistic approach to understand the differences and complementarities of various technologies and systems that incrementally permeate industrial processes. Indeed, extant research outlines specific technological developments

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and paradigms and how they are integrated and influence AEC. Thus far, no study has adopted a step-back approach or provided a constellation of the entirety of automation research in AEC. It is imperative to gain a systems birds-eye understanding of how technologies are interrelated and the macro impact and implications for AEC and beyond. This holistic approach is afforded through large-scale dataset analyses and mapping. To the best of our knowledge, there has been no attempt to provide this overarching networking map of the literature on automation in AEC yet. This study aims to map the state of the literature on automation in AEC and thereby be of value not only to those researching automation and its composition of a variety of distinct technological and system classes within AEC, but also to practitioners and policymakers in shaping the future of AEC.

Our review adopts scientometric methods, which have been effective in research of large intra and interdisciplinary domains in the past decades. In offering literature reviews, scientometric methods most often utilize software that positions and clusters terms, themes and research directions on the basis of algorithms, thereby offering unbiased, transparent and replicable results. These features are undoubtedly of value in providing robust and reliable results in mapping the literature. Therefore, scientometric methods allow researchers to gain a birds-eye perspective on the scholarship, in this case, automation in AEC, in which all published academic research on the topic is arranged under one map with distinct research streams. This permits an interdisciplinary perspective on the topic, thereby ensuring a holistic outlook and a more comprehensive understanding of the phenomenon to be studied (Donthu *et al.*, 2021; Klarin, 2019; Rafols *et al.*, 2012). Through this approach, the study of the themes and research streams will uncover areas in which research is abundant or scant, allowing the researcher to derive a deeper understanding of the subject's breadth and limitations and as a result, suggest avenues for more tailored research directions (Ahmi *et al.*, 2019; Nazarov and Klarin, 2020; Rossetto *et al.*, 2018).

Overall, this review contributes to the existing research in three ways. First, our study aims to provide a general overview of automation in AEC literature from an interdisciplinary perspective. This review finds that there are three established research directions: technological frontiers, project monitoring and applied research in AEC. Thus, research in the field is largely oriented toward technological advancement and application of automation in the field, and that literature lacks aspirations to develop a distinct theory of automation in AEC. Furthermore, the review shows the lack of integration of the disparate literature from a variety of disciplines into a more consolidated body of literature. Second, our study provides a multilevel, multistage integrative model that outlines the causal network of potential precursors, processes and outcomes of automation in AEC. In doing so, we attempt to identify the extent to which automation in AEC is characterized by clearly defined boundary conditions, identification of explanatory mechanisms and other attributes of a good theory. Third, we underline employee well-being, business sustainability and social growth outcomes of automation and provide several managerial implications, such as the strategic management approach, ethical management view and human resource management perspective. Through this, we seek to respond to the Sustainable Development Goals (SDGs) (i.e. decent work and economic growth, industry, innovation and infrastructure, and responsible consumption and production) proposed by the United Nations as this becomes more prevalent for the industry and all levels of society in general.

The paper is arranged as follows. The first part provides a research background to automation in AEC and justifies the need for an integrative review. Second, we explain the scientometric review steps, including identifying a research question, review ranges, search items, and exclusion and inclusion criteria. Third, we present the scientometric review findings and discuss three distinct research clusters. Fourth, we offer an integrative model that underlines the multistage and multilevel nature of automation in AEC. Fifth, we provide theoretical and practical implications, research limitations and diverse suggestions for future studies. Finally, the conclusion section summarizes the contributions of this paper.

2. Background to the automation in AEC and the need for an integrative review

There have been numerous insightful literature reviews published on the pertinent topics of AI, building information modeling (BIM), blockchain-based systems, cyber-physical systems (CPSs), industrial Internet of things (IIoT), robotics, additive manufacturing and other technological advancements relevant to the AEC industry. For example, most recently, Zhang *et al.* (2022) demonstrated the progression of BIM from implementation in design to practical application in construction and maintenance, which is necessary to ensure seamless interaction between technological systems and BIM for the efficient workflow of automated design, virtual production simulations, robotic operation and knowledge transmission. In terms of AI, Darko *et al.* (2020) observed that genetic algorithms, neural networks, fuzzy logic, fuzzy sets and machine learning are the most adopted methods to derive project management, optimization, resolution of uncertainties and simulations in AEC. This finding is somewhat supported by Pan and Zhang (2021b) who assessed research of AI in construction engineering and management and demonstrated that AI will eventually lead to (1) modeling and pattern evaluation, (2) prediction formed on historical data, including risk assessment, cost, timelines, productivity, safety, constructability and other variables, as well as (3) optimization of processes. Similarly, McNamara and Sepasgozar (2021) studied the impetus of smart contracts built on blockchain technology in which the overall benefits of adopting iContracts include better management of resources and the reduction in costs, project durations and payment disputes. In regard to robotic technologies in AEC, Gharbia *et al.* (2020) demonstrated the prevalence of additive manufacturing, automated installation, assembly and bricklaying systems, with scant research on integrated robotic construction sites indicating the nascency of robotics in AEC.

Despite a rich multidisciplinary approach in which scholars from different disciplines offer developments and solutions, there is a lack of an integrated interdisciplinary overarching outlook on the state of automation in AEC. A comprehensive literature review of all AEC-related technologies and their impacts is necessary as there is a need to provide a broad systems perspective on the topic. Indeed, studies such as Jin *et al.* (2018) and Manzoor *et al.* (2021) state the need for comprehensive overarching reviews of digital technologies under one umbrella. A single overarching review allows to identify potential synergies, trade-offs and interconnections between different technologies, their impacts and the wider socio-technical system (Galvin *et al.*, 2021; Inkizhinov *et al.*, 2021). Furthermore, a comprehensive review is ideal in identifying gaps in knowledge, highlighting areas for further research and supporting informed decision making (Klarin and Suseno, 2022). Literature reviews that are focused on specific technologies may provide a deeper understanding of a particular technology and its impact, but they lack the broader context and can miss important inter-relationships and systemic effects.

By providing a comprehensive systems overview of the topic this review aims to fill several gaps in the current disparate literature of technologies in AEC. First, previous reviews have focused on a single technology or clustered technologies, but there has been no single overarching, analytical and forward-looking review of automation that integrates AI, robotics and other technologies into a comprehensive map of automation in AEC. This is a considerable lacuna because different automation technologies could exert distinct impacts on AEC workers and bring divergent opportunities and threats to AEC. Therefore, a comprehensive review may facilitate a more complex and generic understanding of this field. Second, prior literature was concerned with limited aspects of automation (e.g. factors and outcomes). Nevertheless, they downplayed the dynamic interactions between multilevel factors, outcomes and processes of automation technologies in AEC. Our holistic review aims to fill the gap by highlighting the multilevel and multistage nature of automation in AEC.

Third, past studies have mainly mobilized a technological view to capture automation as technological advancement. Nonetheless, few studies have adopted a managerial perspective to explain how to manage automation to improve outcomes across levels (individual, firm and societal levels). This may be problematic because a managerial view can help us address the United Nations' SDGs, which include diverse individual- and societal-level goals, such as Goal 8 ("Promoting sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all"), Goal 3 ("ensure healthy lives and promote well-being for all at all ages"), and Goal 9 ("building resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation") (United Nations, 2022). Thus, this paper aims to provide an overarching outline of automation in construction literature, which useful to those new to the field and those interested in comprehending the interdisciplinarity of the scholarship (especially from a managerial perspective). This scientometric analysis is then complemented by an integrative model of the scholarship to emphasize the multistage and multilevel nature of automation.

3. Developing a systems perspective on automation in AEC

There is a wide range of literature review approaches (see for example, Grant and Booth, 2009), among which systematic literature reviews (SLRs) built on evidence-based approaches in medical science (Tranfield *et al*., 2003) have gained recognition and acceptance across all sciences in the recent decade. Considering the variety of aims and objectives in conducting SLRs, there is a variety of systematic review approaches dependent on the objective of a study. Manual systematic reviews rely on expertise of researchers and are thereby prone to human error or even bias. Systematic reviews can also be quantitative in nature, for example, the preferred reporting items for systematic reviews and meta-analyses (PRISMA) methodology offers a minimum reporting set of items in conducting systematic and meta-analysis reviews (PRISMA, 2022). PRISMA is accepted as a review method to identify, select, appraise and synthesize studies, mostly in medical sciences. While using PRISMA, the study findings somewhat fall secondary to the robust methodology reporting required in each section, beginning from the title and ranging to the implications of the study [1], rendering PRISMA inadequate for integrative reviews that place the findings at the core. In contrast, this scientometric study adopts an exploratory approach to identify the broad scope of the literature, the gaps and directions for future research, which falls outside the boundaries of other quantitative reviews. Thus, we turn to scientometric content-based analyses.

Recent advancements in scientometrics allow the capture of large volumes of data and parse these through specialist analysis tools to gain a systems view of a particular set of published data (van Eck and Waltman, 2014; Klarin, 2019). To provide a taxonomy of the vastly interdisciplinary topic of automation in AEC literature, we employ scientometric research methods, which provide a birds-eye view of the field and allow us to bridge gaps between the variety of disciplines. We utilize VOSviewer, a scientometric mapping software, that demonstrates relationships between indicators on the basis of citation, co-citation, coupling, or co-occurrence analyses in a visual map (van Eck and Waltman, 2014).

The contribution of this study is built on the methodological rigor with which we approached this pertinent discussion. Our approach to conducting a scientometric review is complementary to the commonly published reviews built on traditional content analyses of the literature (for example, Edwards *et al.*, 2022; Melenbrink *et al.*, 2020; Pan and Zhang, 2021a). Simultaneously, the approach here is unique in comparison to existing published review studies. While literature reviews contribute to the field, a scientometric review offers more comprehensive insights through an interdisciplinary systems perspective of automation in AEC. First, a scientometric review provides a holistic approach because it involves a wide coverage of scholarly work, in our case 1,871 publications. Such extensive review built on a large number of published work allows the bridging of research gaps between disparate disciplinary boundaries (Hu and Zhang, 2017; Rafols *et al.*, 2012), enabling a more overarching understanding of the chosen research domain. In this sense, the scope of the scientometric review is broad enough to enable knowledge accumulation, yet specific enough to illustrate research streams in existing automation in AEC scholarship. Indeed, it is imperative for interdisciplinary researchers and those who are relatively new to the field to gain a holistic systems view of the entire interdisciplinary automation in AEC scholarship to identify how various disciplines in the field of study are structured and related to each other.

Second, a scientometric review provides an objective analysis of the extent of work in automation in AEC literature in a systematic manner. Our approach, using a scientometric review, provides both thematic and semantic analyses of the topic, including, for example, the indication of top trending and highest impact articles. Compared with traditional reviews that may be open to subjective presentation and interpretation of data, scientometric methods rely on complex algorithms, enabling an unbiased outlook of the research topic. As such, the findings are objective, consistent, transparent and reproducible (van Eck and Waltman, 2014).

Third, a scientometric review allows the uncovering of interdisciplinary research gaps. The visual representation of scientometric mapping offers a clearer and richer representation of the entire automation in AEC literature with depictions of research streams and topics, thereby highlighting larger and smaller themes excluding themes that have received less attention, hence, indicating gaps in the literature. Essentially, scientometric mapping facilitates a holistic visualization of a particular research domain that could highlight the trends of the scholarship over time and those themes that are underrepresented. The underrepresented themes offer excellent opportunities for research.

In conducting this scientometric review of the literature, this study closely followed the steps proposed by Petticrew and Roberts (2006), Siddaway *et al.* (2019), and Tranfield *et al.* (2003) in conducting SLRs. Furthermore, this review relied on the latest standards in conducting scientometric content-based literature review studies for robust delivery of a systems overview of a particular topic or phenomenon (Donthu *et al.*, 2021; Klarin *et al.*, 2021), in this case automation in AEC. These steps included (a) identification of a research field and a research question, (b) identification of a review range, (c) establishing search criteria and data extraction, (d) dataset screening for exclusion and inclusion, (e) results analysis and their interpretation and (f) discussion of the results.

In the first step, the recognition of the rapidly expanding utilization of automation in AEC stemming from the growth in applied technological advancements raises the question of *"what is the state-of-the-art of automation in AEC and where do we go from here?"*. In the second step, the study aimed to present a large overarching systems perspective built on a substantial body of automation in AEC publications from the two largest structured and extractable academic databases, Scopus and Clarivate's Web of Science (WoS) (Harzing and Alakangas, 2016).

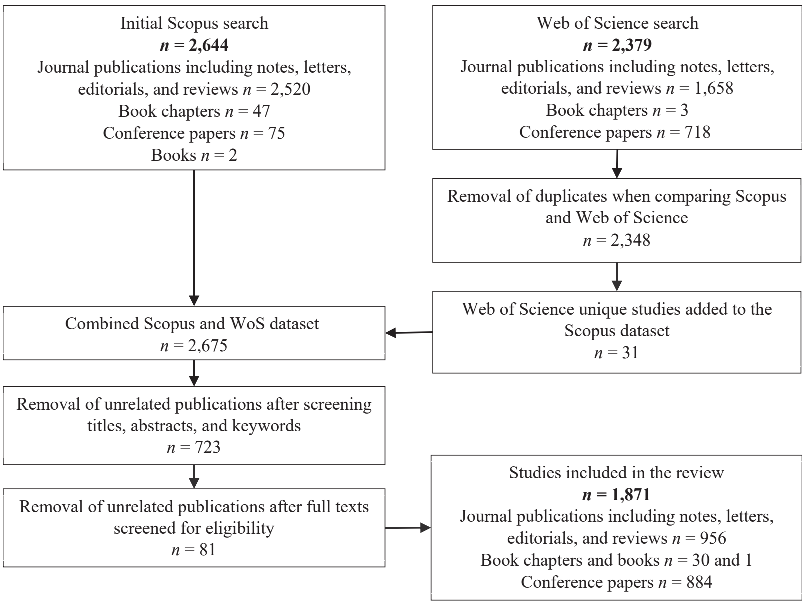
In the third step, we extracted all publications that contained AEC context: *"construction industry" OR "construction engineering" OR "construction management" OR "civil engineering" OR "structural engineering" OR "architectural engineering" OR "architecture-engineering-construction" OR "architecture, engineering, and construction" OR "architecture, engineering and construction" OR "architecture, engineering, and construction"*, which incidentally exceeds that of other studies, including Pan and Zhang (2021a, b). The context search string was combined with the second search string: *"autonomous" OR "automation"* as of March 29, 2022 from the Scopus and WoS databases.

Fourth, we extracted 2,644 studies from Scopus and 2,379 studies from WoS. Considering that there are major overlaps between Scopus and WoS, unsurprisingly most (2,348 of 2,379 studies) of WoS results were already present in the Scopus dataset. After the dataset comparison, it was observed that WoS contained 31 unique relevant results that were not available in Scopus. After reading through the topic areas (titles, abstracts and keywords) of the combined dataset, it was found that 723 studies discussed topics that deviated from automation in AEC discussions. For example, those that were in medical, chemical and other fields that utilized AEC and/or automation terms in a different meaning or as contexts rather than research of automation in AEC (e.g. "muography . . . applied across many fields such as . . . civil engineering"). Finally, having screened full texts of the remaining studies, we removed a further 81 publications. After the inclusion and exclusion phase, the full dataset consisted of 1,871 relevant automation in AEC studies (see Figure 1 for the study selection criteria).

In Steps 5 and 6, VOSviewer software capable of mapping large maps into distance-based clusters built on co-occurrence matrix where items that have high similarities are algorithmically located close to each other (for more details, see van Eck and Waltman, 2010) was selected for an unbiased outlook on the research. A set of items that are closely related to each other were assigned to color-coded clusters. Each item can only occur in one cluster. The clustering technique is discussed in detail by Waltman *et al.* (2010). This study combines bibliometric author, publication, source, institution, keyword and country-based analyses together with content-based analysis made possible through an extraction and linkages of commonly occurring noun phrases to provide an overarching analysis of automation in AEC literature (Klarin *et al.*, 2021).

4. Scientometric review findings

The algorithmic positioning and clustering produced three distinct clusters of research: *red — technological frontiers in AEC, blue — project monitoring in AEC* and *green — applied research in AEC.* A large volume of studies in these three clusters are not theory-informed, and only a handful of papers have a sound theoretical basis, such as risk theory (Ji *et al.*, 2018), complex system theory (Klashanov 2014) and the decision-making framework (Mashayekhi and Heravi, 2020). This is perhaps unsurprising considering that most AEC studies are data-



Source(s): Author's own creation

Figure 1.
Results of the search and study selection criteria

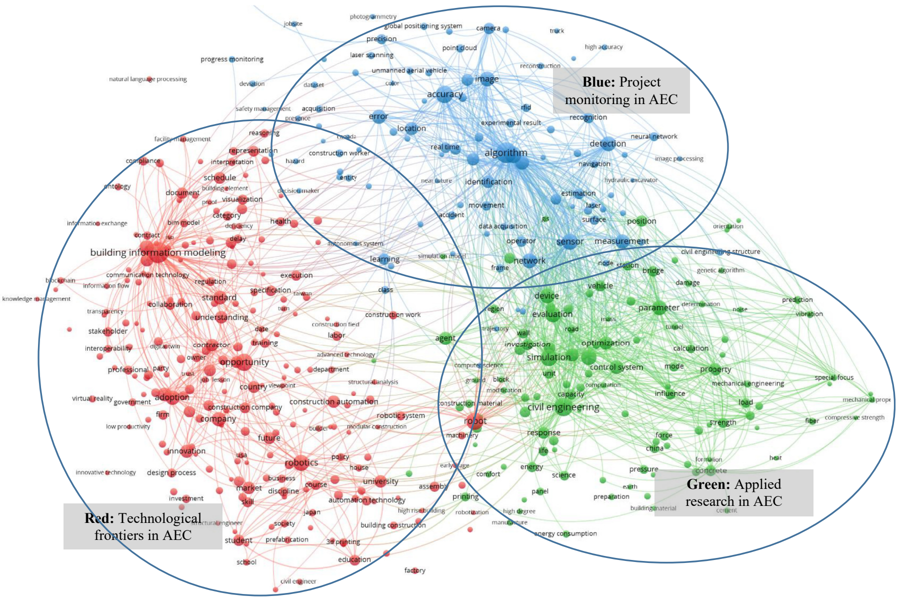
driven, mobilizing the sophisticated modeling approach and advanced experimental methods to contribute to technological innovation (Prabhakaran *et al.*, 2022). We can therefore conclude that each cluster, in its majority, discusses practical technological advances that develop AEC. The practical application is outlined at the outset of each cluster.

The results of the thematic representation built into a software-generated map are presented in Figure 2. Furthermore, Table 1 demonstrates automation in AEC topics that are currently trending, topics that are present in the most cited publications and indicative research disciplines. Table 2 demonstrates the top 15 journals that have published the most prolific research on automation in AEC. To provide the automation in AEC scholarship, it is necessary to discuss each cluster using the themes that are present within, which will provide an overarching understanding of the field to gauge the basic dynamics of existing research on automation in AEC.

4.1 Red cluster — technological frontiers in AEC

This cluster offers technological developments that will eventually enter AEC applications. Therefore, forecasting technological trajectories of AEC leads to a number of visions including (1) user data-driven built environment built on the premises of big data, Internet of things, augmented and virtual realities, sustainability and end user focus, (2) value-driven computational design featuring blockchains, outsourced off-site production, sharing economy, digital twins and data-driven organizations, and (3) efficient construction dependent on algorithms, BIM, lean processes, design and other automation technologies (Ernstsen *et al.*, 2021).

In the current Industry 4.0 emergence, the technologies associated with Industry 4.0 are permeating AEC. These technologies include IIoT (Vrana, 2021), CPSs utilizing robotics and general automation (Bademosi and Issa, 2021; Darko *et al.*, 2020), sensors and wearables, data analytics and algorithms, digital twins (Akanmu *et al.*, 2021; Ozturk, 2021) and BIM (Pan and



Source(s): Author's own creation

Figure 2.
Map of the automation in AEC research

Table 1. Key themes in automation in AEC scholarship

	Top citation impact terms[a]	Top trending terms[b]	Indicative fields
Red – Technological frontiers in AEC	Digital twin(s) Augmented reality Viability Future trend(s) Blockchain Artificial intelligence Natural language processing Automated construction Asset Low productivity Practitioner Deficiency Data management Successful implementation Advanced technology Prototype system Construction operation Facility management	Digital twin(s) Blockchain Low productivity Additive manufacturing/3D printing Digital technology Internet of Things Digitalization Trust BIM model(ing)/technology Employment Construction professional Modular construction Information sharing Natural language processing Information modeling Transparency Lean construction Adoption	Construction management Construction engineering Computer science Innovation management
Blue – Project monitoring in AEC	Video Laser scanning/laser Dataset Computer science Recognition Computer vision Conventional method(s) Neural network Point cloud Tracking Construction progress Classification Safety management Reconstruction Deviation Image Hydraulic excavator Unmanned aerial vehicle	Unmanned aerial vehicle(s)/drone Dataset Machine learning Recall Computer vision Point cloud Video Construction worker Deviation Precision Progress monitoring Reconstruction Neural network High accuracy Jobsite Hazard Structural health monitoring Detection	Safety management Operations management Computer science Construction management
Green – Applied research in AEC	Crack Earth Printing Evaluation Genetic algorithm Shape Optimization Variation Mass Formwork Measure Bridge(s) Complex system Manipulator Wall Security Mechanism Computation	Printing Agent-based modeling Cloud Smart home Autonomous vehicle Compressive strength Concrete structure Crack Formation Reinforcement Formwork Prediction Calculation Damage Numerical simulation Simulation model Shape Comfort	Civil engineering Construction engineering Materials science Computer science

Note(s): [a]Top impact terms appear in the highest average normalized citation articles, in descending order
[b]Top trending terms appear in the most recent articles, arranged in descending order
Source(s): Author's own creation

Outlet	Cluster	Documents	Norm. Cit.*	Av. Cit. per doc
Automation in Construction	Interdisciplinary	217	675.55	48.24
Journal of Construction Engineering and Management	Red	58	164.59	31.31
Journal of Computing in Civil Engineering	Green	61	123.24	29.08
Advanced Engineering Informatics	Red	18	55.74	48.89
Computers in Industry	Red and Blue	6	43.56	105.83
Construction Management and Economics	Interdisciplinary	14	36.73	33.93
Computer-Aided Civil and Infrastructure Engineering	Green and Blue	24	35.85	30.75
Electronic Journal of Information Technology in Construction	Blue and Red	7	25.06	54.00
Construction Innovation	Blue and Red	15	19.56	16.27
Journal of Building Engineering	Green and Red	12	18.70	13.25
Journal of Information Technology in Construction	Red and Blue	11	13.74	15.73
Mechanical Systems and Signal Processing	Blue	5	11.34	57.00
Engineering, Construction and Architectural Management	Red	17	11.02	5.47
Journal of Engineering, Design and Technology	Interdisciplinary	8	9.42	8.13
Journal of Civil Engineering and Management	Green and Red	11	8.85	12.64

Note(s): *Normalized citations indicates the number of citations divided by the average number of citations of all sources in the same year
Source(s): Author's own creation

Table 2. Top 15 journal outlets for automation in AEC by normalized citations per document

Zhang, 2021b; Zhang *et al.*, 2022). Each of these technologies has been discussed within the AEC literature in the past years. Considering the nature of the fourth industrial revolution of the interconnectedness of all these technologies seamlessly, it is necessary to adopt a systems perspective (Nazarov and Klarin, 2020; Turner *et al.*, 2021) on this pertinent topic. Turner *et al.* (2021) offers a three-phase approach (manufacture of modular building components, on-site assembly and construction, and monitoring and control of the finished projects) in the utilization of modular building components interconnected via sensor technologies to intelligent agents. These capabilities remain in research and development stages rather than being applied in AEC extensively (Alaloul *et al.*, 2020; Bosch-Sijtsema *et al.*, 2021; Pan and Zhang, 2021a).

Indeed, while industrialized countries have begun adopting Industry 4.0 technologies, these remain in a state of infancy with little widespread practical applications. For example, Bademosi and Issa (2021) reported that the current adoption of robotic technologies is constrained by uncertainty in the return on investment, high initial investment, and operating and maintenance costs, while cost savings on labor, time and rework entice propositions of robotics. Nevertheless, the technology is considered an exception in AEC rather than a norm. Similarly, additive manufacturing is gaining attention in AEC. However, practical applications are scant because the materials utilized in construction currently are not feasible for additive manufacturing purposes. The challenge is in developing, or at least modifying, materials to suit AEC (Mrazovic and Fischer, 2022). Therefore, Al Rashid *et al.* (2020) provided a thorough review of progresses, research and the limited application of additive manufacturing in AEC. Another example of a technology slowly permeating contracting in AEC is blockchain, which brings significant improvements to payment system efficiencies, transparency and immutability as well as in digitized progress data management (Hamledari and Fischer, 2021; Hunhevicz and Hall, 2020; McNamara and Sepasgozar, 2021).

This cluster also discusses human resource integration and the adoption of technological advancements. Low *et al.* (2021) demonstrated that graduates significantly lack resilience, curiosity, adaptability, entrepreneurial thinking, pursuing convictions and vision soft skills for future work in AEC and possibly beyond. Labor wages often cause cost overruns owing to the lack of consideration for inflation rate increases in budget development. Thus, Alaloul *et al.* (2021) suggested installing automation and technology instead of manual labor that will counter these unexpected cost overruns. As mentioned previously, this cluster provides an outline of possibilities of physical automation in AEC coupled with discussions of BIM applications globally.

4.2 Blue cluster — project monitoring in AEC

In comparison with the red cluster, this research stream offers solutions built on programming and algorithms to bring forth automation within AEC. There are essentially three broad integrated themes within this cluster — safety management, progress and performance monitoring, and the related object tracking on work sites.

In the progress and performance monitoring, unmanned aerial vehicles are gaining research traction owing to their ability to assess construction operations in real time, and map and model capabilities with significant ease compared with traditional on-site inspections and techniques (Irizarry *et al.*, 2012; Keyvanfar *et al.*, 2022). Computer vision methods are increasingly utilized in practice for automatic monitoring and object tracking of construction processes (Wang *et al.*, 2021a, b). Furthermore, highway operations can be enhanced using LiDAR technologies (Gargoum and Karsten, 2021). In related research, RFID technologies assist in automated on-site progress monitoring as well as resource tracking when placing sensors in strategic positions and if sensors are embedded within the equipment (Guven and Ergen, 2021). In regard to machine learning, Slaton *et al.* (2020) observed that hybrid deep-learning architecture consisting of convolutional neural network (CNN) and recurrent long short-term memory networks outperform the baseline CNN in tracking and monitoring equipment performance, and measuring productivity and efficiency of work. However, there is an issue in adopting smart monitoring built on algorithms, which is possible to be resolved through explainable AI that aims to assist users in comprehending and trusting the results and outputs created by machine-learning algorithms (Luckey *et al.*, 2021).

In the construction safety research, image classification is often used to detect potential safety issues. For example, Dung and Anh (2019) successfully demonstrated the uses of deep convolutional networks that trained on a set of 40,000 images to identify cracks with an approximate 90% precision rate. However, it remains challenging to gather sufficiently large datasets from construction in developing machine-learning solutions in object detection in real time (Xiao and Kang, 2021). There is also a significant stream of research that points to the utilization of radio frequency remote sensing that produces visual and audio signals in identification (Teizer *et al.*, 2010; Wu *et al.*, 2010; Yap *et al.*, 2021). Furthermore, the use of video feeds including closed-circuit television, video cameras and webcams coupled with algorithmic risk assessment is another way to monitor and implement related safety measures in practice in construction (Chi and Caldas, 2011; Guo *et al.*, 2021). In the latest technologies, satellite-based technologies are capable of structural health monitoring of large infrastructural projects, such as extensive transport networks, which has the potential to be integrated into structural health monitoring systems (Macchiarulo *et al.*, 2022). Increasingly, attention is being paid to prevention measures and risk assessment using information technologies. For example, Rodrigues *et al.* (2021) proposed plugins for BIM that are capable of identifying such issues as fall detection hazards and automated placement of safety systems. There are a number of available review studies examining common algorithmic approaches in AEC for those interested in the expanded discussion (Darko *et al.*, 2020; Luckey *et al.*, 2021; Pan and Zhang, 2021a).

4.3 Green cluster — applied research in AEC

This research cluster offers solutions built on actual applications and simulations of technological advancements in AEC, and therefore, is more practice-oriented rather than theoretical in nature. While the red cluster research mainly considers technological frontiers and how these will change AEC in future, this cluster takes a shorter timeframe adoption curve and offers solutions to the current issues in AEC. Some of the proposed solutions are already being implemented in AEC practice compared with mostly conceptual and propositional research in the red cluster. For example, in recent research, Thneibat *et al.* (2022) utilized agent-based modeling to demonstrate constructors' adoption of value management to be effective through the extensive use of mass media, incentives including tax deductions and word-of-mouth promotions. Dorrah and Marzouk (2021) offered a model for an assessment of the sustainability performance of buildings according to occupant-measured metrics — energy consumption, flow patterns and satisfaction — thereby rendering this model an effective decision support system for building layout. Machine learning using convolutional neural networks coupled with wavelet-based multiresolution analysis has been shown to have excellent results in early detection of cracks in concrete with approximately 98% accuracy (Arbaoui *et al.*, 2021). Civil engineering is increasingly adopting algorithms to develop urban infrastructure considering the complexity of institutions and other environmental factors. De Luca *et al.* (2021) suggested utilization of computational design to calculate optimal solar envelopes in dense urban environments, considering regulatory constraints, which offers larger building masses than the conventional method. Wang *et al.* (2021a, b) utilized Bayesian factor analysis for damage detection of structures. This method accurately identifies environmental factors and structural damage, even when changing environmental data are unavailable. Furthermore, we are inevitably moving toward algorithm-based solutions for building design and facilities management. Algorithms are shown to be more efficient in emergency event scenarios of crowded buildings, such as passenger terminals in identifying issues, evaluating performance and managing uncertainties (Tang *et al.*, 2021).

Research into the use of modern technologies offers significant advancement potential for construction materials. For example, additive manufacturing allows printing concrete that is lightweight, sustainable, minimizes waste and generally improves material efficiency by replacing sand with cork (Craveiro *et al.*, 2020). In another cement printing study, 40% worth of coarse aggregates were added in the printing process that could serve as supporting materials (Yu *et al.*, 2020). Sustainability concerns also bring forth innovative materials such as magnesium oxide structural insulated panels, which beside being resistant to fire, water, mold and insects, are also shown to be more sustainable through on-site manufacturing, domestic sourcing of magnesium oxide and elimination of oriented strand boards (Li *et al.*, 2018). Research into electromagnetic noise reduction materials and techniques to measure these demonstrates that panels containing over 15% metallic fibers and those reinforced with grids with a sieve area below 150 mm^2 have higher electromagnetic values (Quintana *et al.*, 2018). Reichenbach and Kromoser (2021) reviewed the current trends and developments in construction material in their state-of-the-art review.

Furthermore, this cluster discusses driverless technologies in AEC. Adoption of autonomous vehicles faces a number of challenges, including cyber security, infrastructure, digital mapping issues as a facet of technological barriers, safety, cost and customer readiness as societal barriers, and lack of legislation as legal barriers to a widespread adoption in AEC and beyond (Edwards *et al.*, 2022; Saeed *et al.*, 2021). Nevertheless, joint stakeholder approaches are being adopted to prepare road infrastructure for autonomous vehicles because such simulations, including the use of 3D point cloud data, are run to assess highway readiness for driverless vehicles (Gouda *et al.*, 2021).

Table 3 summarizes technologies that aid and lead to automation within each cluster, each of these appears in at least 10 publications. The authors note that although themes and

Red – Technological frontiers	Blue – Project monitoring	Green – Applied research
(Construction) automation	Information	(Numerical) simulation
(New/digital/innovative/computer) technology	Algorithm	Machine
Building information modeling (model/technology)	Experiment(al result)	Automation system
Software (tool)	Tracking	Data acquisition
Robot(ics)	Camera	Energy consumption
Infrastructure	(Computer) vision	Automatic control system
Database	Machine learning	Fiber
Prototype	Construction equipment	Autonomous vehicle
Internet	Hardware	Mobile robot
Information (communication) technology	Map(ping)	Computer science
Computer Aided Design	3D model	Agent-based model(ing)
Artificial intelligence	(Wireless) sensor network	Genetic algorithm
Digitalization	Automated system	Geographic information system
3D printing	RFID	Building material
Additive manufacturing	Point cloud	Cloud
Machinery	Laser scanning	Energy saving
Internet of Things	Unmanned aerial vehicle	Finite element analysis
Augmented reality	Image	Sensor technology
(Design/building) automation	Video	Smart home
Blockchain	Structural health monitoring	
Mechanization	Global positioning system	
Information systems/management	(Progress/real-time) monitoring	
Lean construction	Drone	
Automated construction	Automatic identification	
Digital twin	Photogrammetry	
Modular construction	Truck	
Intelligent building	Dataset	
ISO	Hydraulic excavator	
Information exchange		
Robotization		

Table 3. Technological domains of automation in AEC in descending order

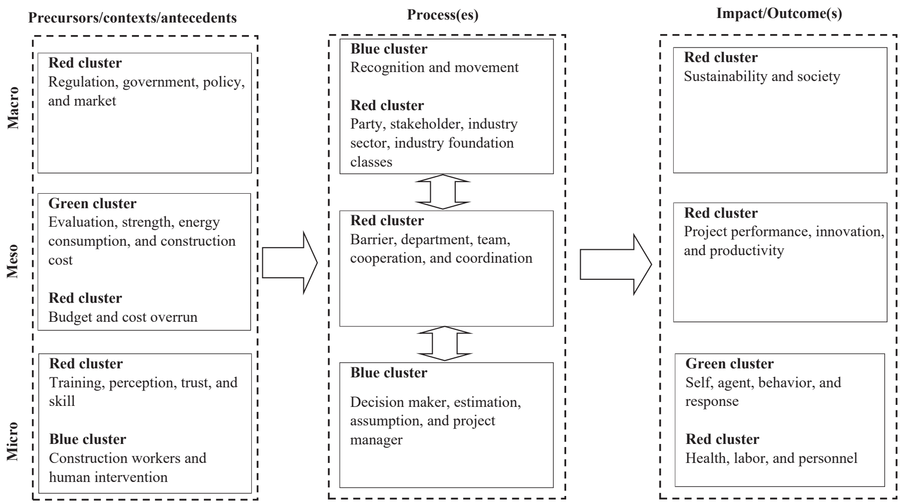
technologies are associated with one cluster, other clusters may discuss similar themes and technologies within a different context. For example, while algorithmic solutions are at the core of the blue cluster, the green cluster discusses applied research that utilizes algorithms in civil and mechanical engineering research. The red cluster discusses algorithms as a game changer in AEC from more conceptual and theoretical stances.

The brief outline of the research clusters above demonstrates the lack of a well-defined cumulative research flow. The contributions are piecemeal conceptual rather than theoretical or are generally descriptive rather than explanatory. For instance, there is a lack of research into micro (individual) or macro (institutional) level moderator and mediator variables influencing the adoption or facilitation of automation in AEC. Furthermore, the research streams outlined above have largely emerged in relatively isolated silos as demonstrated through the algorithmic clustering and supported by a lack of cross citations across the clusters. These research clusters do not interact and do not build off one another into a consolidated research field. Therefore, this study combines the disparate research into a multistage multilevel model that aims to integrate the fragmented research into one consolidated framework that conforms to the pertinence of United Nations (UN) SDGs' integration into the industry and beyond.

5. A multistage and multilevel model of automation in AEC

To develop a comprehensive and dynamic understanding of automation in AEC, we established an integrative model that underlines the multistage and multilevel nature of automation (see Figure 3). This model advances the literature on automation in AEC in two ways. First, most previous studies, especially those published in AEC journals, have regarded automation as a simple and static entity without teasing out the development and evolvement of automation. To fill this gap, we have taken a temporal perspective to capture the three core stages of automation: pre-formation, processes and post-formation. At the pre-formation stage, we investigated manifold cross-level factors that may shape automation systems. At the processes stage, we highlighted the complex processes through which automation is designed, implemented and standardized. At the post-formation stage, we explored various outcomes of the implementation of automation. We suggest that the post-formation stage should not only identify short-term outcomes, but also focus on how to sustain the adoption of automation to fully reap its benefits in the long term.

Second, as discussed in Section 4, most of the past research has examined automation at the organizational (meso) level, focusing on the influences of automation on organizational productivity. However, different employee well-being (micro) outcomes and societal (macro) outcomes remain less explored. This may be a significant knowledge gap considering that academics and practitioners have been devoting burgeoning attention to SDGs suggested by the UN. The SDGs include many individual-level and societal-level goals, such as "promoting sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all" and "building resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation" (United Nations, 2022). These goals can be achieved through the successful implementation of automation in AEC. Our study aims to manage automation in AEC at micro, meso and macro levels, and identify a wide variety of stakeholder groups that are actively engaged in the automation of the sector. We suggest that the automation system may minimize the occupational risks of construction workers and therefore promote the health of individual employees. In addition, managers across departments must cooperate to effectively implement automation in AEC. Moreover, government and policymakers, AEC industries and companies should actively take action to



Source(s): Author's own creation

Figure 3. Multilevel and multistage analysis of the scholarship

standardize and improve automation technologies at the societal level to promote sustainable industrialization and enhance social innovation.

5.1 Pre-formation stage — precursors

The qualitative analysis of the findings of the scientometric review demonstrates that extant literature investigates manifold factors or precursors that facilitate or hinder automation in the pre-formation stage. Past studies have touched on these factors at a single level, while this study is the first attempt to make a holistic assessment of these factors at three different levels and across the three stages.

At the micro level, current research is concerned with a number of individual-level predictors of the use of automation technology, which are discussed in the red cluster (e.g. *training, perception, trust* and *skill*) and in the blue cluster (e.g. *construction workers* and *human intervention*). Individuals play a critical role in designing, implementing and maintaining automation systems. Employees' mindsets, skills and competencies could facilitate the establishment and development of automation systems (Hammontree and Aydin, 2020; Low *et al.*, 2021). As Yahya *et al.* (2019) asserted, workers' perceptions of and trust in new automation may lead to the successful adoption of robotics. Therefore, the construction organization should provide a range of training programs and human–robot interaction opportunities to increase employees' perceived safety (You *et al.*, 2018). Adami *et al.* (2022), for instance, reported that VR-based training can significantly improve construction workers' trust in the robot and can promote workers' self-efficacy and situational awareness. Construction workers' positive attitudes toward robots are likely to increase the use of automation on construction sites. These individual-level variables need to be examined as moderators and possible mediators in the adoption of automation in AEC.

At the meso level, previous studies have explored several organizational factors influencing the implementation of automation. The key terms in the red cluster (e.g. *budget* and *cost overrun*) and the green cluster (e.g. *evaluation, strength, energy consumption* and *construction cost*) can denote these organizational-level precursors. Bademosi and Issa (2021), for example, reported that long-term cost savings may facilitate the decision to utilize automation technologies, while the initial investment costs could hinder the utilization of automation. In effect, the cost-benefit analytical approach is often employed to elucidate whether AEC organizations should adopt automation technologies (Gregory and Kangari, 2000). Specifically, the company needs consider both the organizational benefits (adding value) and the potential costs through the introduction of automation for the company. If the long-term benefits outweigh the temporary costs/risks, the company is likely to use automation technologies (Choi and Ibbs, 1990). Because research within this level is built on case studies, little is known at the population level about the common precursors and the resulting performance or failure rates of automation adoption and whether the adopting organizations' performances differ from those of counterparts that have not adopted automation.

At the macro level, previous research has focused on a set of external pressure and institutional drivers that have resulted in the technological changes in AEC, such as governmental support, regulatory compliance, market development, the industrial revolution and legal requirements (Delgado *et al.*, 2019; Turner *et al.*, 2021). The red cluster explicitly denotes these macro-level factors, including regulation, government, policy and market. Indeed, the institutional-level precursors may influence, if not determine, the introduction of automation in AEC. As Nnaji *et al.* (2019, p. 499) eloquently argued, "the adoption, implementation, and the extended use of technologies in the construction industry is a complex phenomenon, impacted by multiple industry-specific variables". For instance, the fourth industrial revolution or Industry 4.0 (Nazarov and Klarin, 2020) has created contextual and technological requirements for robotics and automation. Specifically, Industry 4.0

requires future employees in the construction industry to improve soft skills (e.g. *mindsets* and *competencies*) related to big data and automation. Therefore, three key institutional-level parties (the government agency, universities and industry) should play a critical role in helping future graduate students prepare for the significant transformations brought by Industry 4.0 (Low *et al.*, 2021). More specifically, to adapt to Industry 4.0, many countries have initiated a series of legislative mandates, research projects and funding programs to facilitate the digitalization and automation of AEC (Oesterreich and Teuteberg, 2016). The research thus far largely describes the possibilities of automation but lacks in its capacity to draw out more definitive conclusions on the actual measurable impact of automation for industry, society, environment, or stimulating institutional changes.

5.2 Formation stage — processes

Our review moves beyond previous scientometric and systematic review studies in that we investigate the process nature of automation in AEC. Most prior literature has treated automation as a technological construct, paying scant attention to the internal dynamics of automation processes. On the basis of the qualitative analysis of extant literature, we argue that automation is not a static entity. Rather, it involves three complex and interconnected processes (decision-making, implementation and standardization) across levels. The three distinct processes are by no means working in silos and should not be considered in an isolated, exclusive and pigeonholed manner. We suggest that three specific processes are likely to complement and reinforce each other, having joint effects on employees, organizations and society. For instance, the "implementation" of automation can assist both individuals and departments/teams in the "decision-making" process. Thus, a holistic perspective is needed to investigate all three processes and their interconnections.

In addition, various groups of stakeholders within and outside AEC are proactively engaged in these processes. More specifically, first, project managers and senior management may utilize automation technologies to calculate project benefits and costs and make decisions. In other words, automation can assist managers to formulate decision-making processes. Second, diverse managers across departments/teams need to work together to ensure the successful implementation of automation. Third, once automation systems are effectively executed at the organizational level, a wide range of stakeholders within and outside AEC (e.g. the state, governmental agencies, industry and firms) seek to standardize, legitimize and promote these technological advances at the societal level. Below, we will discuss these three processes in more detail.

At the micro level, the blue cluster (decision-making) mainly explains practitioners' decision-making process that is assisted by the adopted technology. Key terms include *decision maker, estimation, assumption* and *project manager*. Traditionally, academics and managers have considered AEC production a predictable entity. Thus, project managers have tended to make decisions primarily on the basis of their past work experience, personal assumptions, professional knowledge and cognitive schemes. That is, the previous decision-making process was subjective and experience oriented. Nonetheless, in the recent decade, managers and engineers are more inclined to use the data-driven approach to make decisions because it is more effective, accurate, unambiguous and transparent (Raco *et al.*, 2021). For example, Mashayekhi and Heravi (2020) developed an automated decision-making framework by BIM, management information systems and simulation tools. This data-driven comprehensive framework, as Mashayekhi and Heravi (2020, p. 2) suggested, can be mobilized to select "the optimized combination of smart building's equipment". Similarly, Desgagné-Lebeuf *et al.* (2020) established a decision support system that assists project managers to gain access to various tools and select the one that can best meet their interests and needs.

At the meso level, the red cluster (implementation) highlights the process through which automation systems are implemented within the construction firm. The key terms denoting the organizational-level implementation processes include barrier, department, team, coordination and cooperation. In effect, there is a wide variety of challenges and barriers throughout the implementation processes (Mahbub and Humphreys, 2005). Lehtovaara *et al.* (2022) demonstrated that managers and the production crew might have distinct perceptions of production control. The gap between their perceptions could create barriers to the effectiveness of production control. In addition, during the implementation period, communications across distributed teams might be ineffective owing to the lack of formal structures (Ingawale, 2007). To address these barriers, managers at different levels (i.e. frontline supervisors, middle managers and senior management) and managers in different departments/teams ought to coordinate closely to ensure the effective and consistent implementation of automation technologies (e.g. timelines, project cost management, quality assurance and personnel arrangements). For example, middle managers should develop professional knowledge about team-based management and become active coaches. In addition, construction workers need to have a holistic understanding of the entire autonomous construction process (Buch and Sander, 2005).

At the macro level, the red and blue clusters dominate, examining the standardization process. The standardization process refers to the process through which automation is institutionalized and socialized, including social recognition and the establishment of appropriate standard systems. In the blue cluster, macro-level terms (e.g. *recognition* and *movement*) describe the social recognition of automation. Indeed, social recognition is likely to create an innovative industry environment that fosters the development, movement and standardization of automation in AEC. Moreover, in the red cluster, key terms including *party*, *stakeholder*, *industry sector* and *industry foundation classes*, are evident, emphasizing manifold stakeholders/parties across fields that are involved in the standardization of automation technologies. For example, the Chinese construction industry sought to establish an appropriate standard system to ensure the sound development of information technology (Shang *et al.*, 2004). This indicates that the standardization process of automation is not only a technological process, but also a societal and institutional issue. We suggest that automation processes cannot be achieved by a specific single firm or engineer. Instead, the collective efforts of multiple stakeholders within and outside AEC are required for the successful standardization of automation.

5.3 Post-formation stage — outcomes and implications

Our review of the current research shows that much attention has been paid to an eclectic range of outcomes and effects of automation in the post-formation stage. These consequences can be classified into three groups on the basis of their levels of analysis. It is worth noting that the majority of previous research has discussed short-term outcomes of automation at the individual and organizational levels, whereas long-term outcomes (e.g. long-term business success, sustainable innovation, societal and environmental benefits) remain underresearched. This may be a considerable gap because one of the SDGs suggested by the UN is to "build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation" (United Nations, 2022). We maintain that the long-term benefits of automation across levels should be the important target of the post-formation stage. A critical question may be how to sustain the implementation of automation to achieve its benefits in the long term.

At the micro level, prior literature has documented how automation technologies make a great contribution to individual-level outcomes (Joshua and Varghese, 2014; Sherafat *et al.*, 2020), which are demonstrated in the red cluster (e.g. health, labor and personnel) and the green cluster (e.g. self, agent, behavior and response). These individual-level outcomes are of particular importance for two main reasons. First, AEC is characterized by labor intensity: a large number of manual workers are engaged in different phases of AEC projects (Pan and Zhang, 2021a). From the perspective of business performance, a deeper understanding of manual workers' behaviors and responses can help an AEC organization better manage these workers and motivate them to improve project performance and productivity. Second, AEC workers are plagued with diverse occupational safety and health issues (Teizer, 2016). From an ethical perspective, it is timely and critical for both academics and practitioners to pay special attention to the well-being of workers. For instance, Choi *et al.* (2021) developed an automated noise exposure assessment model for the safety and health of construction workers, which is designed to protect the health of workers from excessive noise exposure.

At the meso level, automation technologies have been argued to result in increased organizational profit and improved project performance (Hsieh, 1997; Mahbub, 2020). Terms including *project performance, innovation* and *productivity*, are discussed at the organizational level in the red cluster. Although AEC is an important sector of employment, its productivity lags other industries (Rao *et al.*, 2022; Zhou *et al.*, 2021). Over the past decades, both researchers and practitioners have been devoting their effort to addressing the productivity gap (Desgagné-Lebeuf *et al.*, 2020). O'Connor and Yang (2003), for example, reported that construction companies seek to improve organizational and project performance by implementing automation technology. Their results confirmed that the utilization of automation technology has a positive impact on two core dimensions of project performance, a project's cost and schedule success. Similarly, Chen and Luo (2019) revealed that the location accuracy of autonomous job site monitoring technologies can improve safety monitoring performance. Overall, these studies focus predominantly on the benefits of automation for AEC firms, while downplaying the potential risks rooted in the automation technology. In addition, past research has focused mainly on the short-term benefits of automation, but has relatively neglected how to maintain and maximize these benefits in the long term. Hence, it is imperative to pay greater attention to the long-term organizational benefits of the adoption of automation, such as long-term business success and sustainable innovation in the post-formation stage.

At the macro level, a small number of studies have identified the long-term benefits, such as social, political, economic, environmental and legal outcomes of automation (e.g. Vassallo, 2017). The key terms in the red cluster (e.g. *sustainability* and *society*) are examples of these macro-level consequences. Parveen (2018), for example, depicted a set of legal and regulatory issues (e.g. civil wrongs, cyber risks and criminal liability) that are originated from AI, automation and robotics in the construction sector. Hence, ethical guidelines and legislative frameworks are required to reach a balance between technological advancements and the protection of human rights. In a similar vein, Oesterreich and Teuteberg (2016) outlined the economic, social and environmental outcomes of automation in AEC. For example, the introduction of automation could minimize construction waste, reduce carbon dioxide emissions and improve environmental sustainability.

6. Discussion and future research directions

As discussed in previous sections, current literature has predominantly captured automation in the AEC fields. Most have adopted a technological perspective to regard automation as technological advancement (see the three clusters). Furthermore, as indicated in our multilevel and multistage model, past research has focused primarily on the short-term organizational benefits of automation, but has ignored the long-term impacts across levels. Therefore, we encourage future research to move beyond AEC domains and embrace a managerial view to investigate how to manage automation to lead to long-term benefits at the individual, organizational and societal levels. The following research directions also seek to respond to the UN's human-centered sustainable development agenda, including "promoting full and productive employment and decent work for all", "ensuring sustainable production patterns", and "promoting inclusive and sustainable industrialization and fostering innovation" (United Nations, 2022).

6.1 Theoretical implications

6.1.1 Strategic management approach. The strategic management approach emphasizes the role of organizational alignment in enhancing performance. Specifically, an organization's business strategy should be aligned with the internal structure (internal alignment) and the external environment (external alignment). Desirable organizational performance outcomes are the result of internal and external alignments (Powell, 1992).

Over the most recent decade, there are few, if any, studies touching on the alignment of automation systems and organizational strategies (Hiekkanen *et al.*, 2013). As discussed previously, past literature has regarded automation as a technological entity, while undermining its business and managerial implications. Thus, it is perhaps not surprising that the current conceptualizations of business–IT alignment remain insufficient and superficial (Hiekkanen *et al.*, 2013). Therefore, we encourage future research to adopt a strategic management approach to identify the strategic fit of automation.

In terms of internal alignment/fit, future studies may have an in-depth appreciation of the internal fit between automation systems and the entire set of business strategies of an AEC company. We believe that automation technologies must not be considered a single system that is in isolation from the overall strategy of an AEC firm. Instead, automation technology ought to be viewed as an indispensable component of the overall organizational system. In other words, automation technologies need to be internally connected to business strategies, organizational resources, firm structures and organizational goals to achieve positive outcomes.

In terms of external alignment/fit, we suggest that there should be an external fit between automation systems and the external AEC environment. Hiekkanen *et al.* (2013) called for a more adaptive, dynamic and encompassing research paradigm to tease out the complex strategic context in which the information system is embedded. This is particularly relevant to the AEC context in which inevitable adjustments, occupational injuries and complex operation processes are by no means uncommon (Pan and Zhang, 2021a). Thus, we suggest that future research should examine the strategic alignment of automation systems with increasingly complex contexts to minimize potential risks and maximize project performance.

6.1.2 Ethical management view. Prior research has focused primarily on the positive outcomes of automation technologies, such as improving efficiency, innovation, performance and productivity (O'Connor and Yang, 2003). However, the dark side of the development and use of automation in AEC remains underresearched. This is an important lacuna because automation technologies are likely to generate negative outcomes or unintended consequences. As Prabhakaran *et al.* (2022) suggested, manifold challenges and issues may be associated with the application of advanced technology in AEC, such as ethical issues, and health and safety concerns. To bridge this research gap, future research should take an ethical management view to address the side effects of automation.

As noted previously, a number of legal and ethical challenges (e.g. privacy concerns, cyber risks and criminal liability) have emerged as a result of the utilization of automation and robotics in AEC (Parveen, 2018). For instance, construction workers tend to be faced with physiological and cognitive difficulties in performing real-world duties after being exposed to the virtual system for a long time (Prabhakaran *et al.*, 2022). In addition, the development of blockchain in AEC may give rise to privacy and security concerns in that all users are able to gain access to digital information and history data concurrently. As such, future studies need to pay greater attention to ethical guidelines and administrative policies that are designed to manage these ethical issues.

6.1.3 Human resource management perspective. As one of the largest employment sectors, AEC can provide job opportunities for approximately 7% of the working population in the world (Pan and Zhang, 2021a). Although a large number of workers are employed in AEC, there is a lack of skilled and semi-skilled AEC workers who are able to fully appreciate the advanced technologies (Prabhakaran *et al.*, 2022). This may be a considerable gap given that human–robot interactions require specific professional skills and knowledge. Hence, future research should adopt a human resource management perspective to highlight the added value of human capital to the sustainable development of automation in AEC. For example, future studies may investigate the mechanism through which skill-enhancing bundles of HRM, such as job-based skill training and job rotation (Subramony, 2006), could be deployed to improve AEC workers' tacit and implicit knowledge of automation.

Moreover, future studies may theorize the role of job rotation systems in assisting frontline workers to build a broader skillset. Most construction workers, engineers and managers have specialized knowledge, without a holistic understanding of the overall automation system. Through regularly shifting between two or more tasks or assignments, AEC workers are likely to develop an in-depth appreciation of the different stages or aspects of automation systems, such as project planning, project cost management, decision-making and quality assurance.

6.2 Practical implications

Our study is of great significance to practitioners. First, managers should be aware that automation is not just a technological entity. Rather, it should be aligned with the internal business strategies of an AEC organization and the external AEC environment. For example, the implementation of 3D printing (additive manufacturing) system should be in line with the organizational resources and financial goals because an AEC company needs to invest a significant amount of money in computer-enabled facilities. In addition, blockchains must be formulated to conform to local and global security regulations.

Second, managers are required to appreciate the dark side of automation in AEC. For example, construction workers are inclined to suffer from physical (i.e. headaches, nausea and unnatural postural demands) and psychological problems (i.e. burnout, emotional exhaustion and addiction) while using automation technologies (Prabhakaran *et al.*, 2022). To manage these problems, managers need to implement well-being-oriented management practices (e.g. employee assistance programs) to mitigate employees' health-related issues. This is of practical importance considering that one of the SDGs is to "ensure healthy lives and promote well-being for all at all ages" (United Nations, 2022).

Third, the long-term success of the adoption of automation cannot be achieved without the effort of frontline workers. Hence, AEC organizations are advised to provide frontline workers with a broad range of training and education opportunities to help them develop a fine-grained understanding of automation systems. In doing so, frontline workers, especially those who are less educated, tend to gain an increased sense of workplace safety, be more willing to trust novel robotic systems and appreciate the robot-provided information (Adami *et al.*, 2022).

Fourth, managers should understand that automation can not only resolve an AEC company's performance issues, but can also address many other societal and environmental challenges facing our broader community. Hence, multiple stakeholders within and outside the AEC field (e.g. the government, the public and universities) should work together to sustain the use of automation to reap its benefits in the long term.

6.3 Research limitations

Our review has some limitations. First, rather than focusing on specific single technologies in detail, we investigate the wide scope of automation in general to offer a holistic and comprehensive review of the overall automation research. This might be problematic as we downplay the variety and distinctiveness of various autonomous technologies. Future studies may examine how diverse technologies are adopted at different stages by different professionals to tackle respectively suitable issues. Second, some clusters and themes identified do not significantly engage with theories. The reason is that most prior AEC studies included in our sample are data- or technology-driven instead of theory-informed. Future research may use more diverse theoretical paradigms to provide practical implications. Third, the dataset of publications studied were derived from the search string we presented in Section 3, thereby potentially limiting the analysis. Studies that discuss automation within AEC that do not specifically mention automation or autonomous in the topic areas fall out of the dataset. Finally, this study is only able to provide the "big picture" view of the scholarship based on 1,871 publications, and thereby does not engage with any particular stream of research in detail.

7. Conclusion

In an ongoing process of improving productivity, automation enabling technologies and processes are increasingly being trialed and adopted in AEC and beyond. Based on scientometric methods, this review study provided an overarching view of the state of research on automation in AEC and thereby contributes to the literature in (1) mapping research into three broad research streams with outlines of themes and technological domains (technological frontiers, project monitoring and applied research in AEC); allowing to (2) propose an integrative multilevel multistage model of automation in AEC with the discussion of key stakeholders across levels and stages of automation in AEC, in turn (3) allowing to delineate directions for future research, especially from the managerial perspective. These research directions seek to respond to the UN's human-centered sustainable development agenda, including "decent work and economic growth", "industry, innovation and infrastructure" and "good health and well-being" (United Nations, 2022).

Note

1. See the checklist of PRISMA 2020 Checklist: https://www.prisma-statement.org//documents/PRISMA_2020_checklist.pdf, accessed December 3, 2022.

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