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Review

Construction 4.0 Technologies and Decision-Making: A Systematic Review and Gap Analysis

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Abstract: Construction 4.0 involves implementing advanced technologies in construction projects to achieve higher productivity, safety, and sustainability. However, architecture, engineering, and construction (AEC) professionals are reluctant to adopt Construction 4.0 technologies. Lack of information on Construction 4.0 technologies and poor decision-making lead to the issue being unresolved. As a result, the following research question emerged: What are the current trends and research gaps in the existing research on Construction 4.0 technologies and decision-making? This study aims to review the publication trends in Construction 4.0 technologies and decision-making and pinpoint the gaps in prior research. To achieve the aim, a systematic literature review (SLR) was conducted on published articles using the preferred reporting items for systematic review and meta-analyses (PRISMA) method. A total of 22 articles were carefully selected and reviewed. The findings disclosed four research trends: strengths, weaknesses, opportunities, and threats. Also, the findings suggested that existing research still concentrates on adopting and implementing Construction 4.0 technologies. As a result, the existing research has low exploration in integrating Construction 4.0 technologies and decision-making processes. The study findings could guide researchers and AEC professionals to establish effective decisions in achieving Construction 4.0.

Keywords: Construction 4.0; emerging technologies; decision-making; systematic literature review; SLR

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1. Introduction

The fourth industrial revolution (IR 4.0) has created a paradigm shift in the construction industry toward digital transformation. IR 4.0 has gained the construction industry leader's attention in utilizing modern technologies for collaboration, coordination, and communication to deliver a sustainably built environment. The critical concept in IR 4.0 is machines interconnected via a network or the internet using the next generation of cyber-physical technologies [1]. This includes artificial intelligence (AI), robotics, and nanotechnology. Digital transformation could enhance deliverance in terms of quality, safety, sustainability, productivity, and competitiveness. According to the world economic forum (WEF), digital technology adoption boosts productivity, streamlines project management and procedures, and enhances quality and safety [2]. Therefore, to align with IR 4.0, the construction industry needs to transform significantly by deploying emerging technologies.

The transformation towards a greater level of digitalization has led to a new concept known as Construction 4.0. Construction 4.0 was coined from IR 4.0, originating from the German manufacturing sector [3]. The advanced technologies parked under the IR 4.0 concept include big data and analytics, autonomous robots, simulations, system integrations, the internet of things (IoT), cyber-physical systems, cloud computing, additive manufacturing (AM), and augmented reality (AR) [4]. These technologies are primarily used in the manufacturing industry. The construction sector started digitalization through Construction 4.0, referring to the success of the manufacturing industry. Adopting emerging technologies in construction processes could completely change the physical assets' design, development, and preservation. According to [5,6], digital collaboration across project phases could enhance operational efficiency, the management of project lead times, and waste minimization. It showed that the roles of digital technologies in the construction industry are no longer mere tools. Instead, they fundamentally change the method of running a construction business. Therefore, to thrive in IR 4.0, it is critical to adopt Construction 4.0 technologies.

In recent years, construction projects have become further complex, and budgets and schedule burdens are rising while the quality standards are growing. In the face of such challenges, the construction industry is morally obligated to transform towards digitalization. However, even though digitalization has been a growing trend for years, it is still in its infancy stages and remains scattered and unorganized [7]. Moreover, most construction professionals have been reluctant to adopt Construction 4.0 technologies [8]. This reluctance is due to the nature of the construction industry. These include project complexity, the uncertainty of the external environment, a fragmented supply chain, short-term thinking, and cultural issues 9. Due to these factors, decision-makers have difficulty selecting strategic decisions for technology adoption. They require critical and analytical thinking to establish significant decisions, especially in complex projects. In a worst-case scenario, at the management level, there is a lack of decision tools to select Construction 4.0 technologies in the construction industry [8]. Therefore, it is necessary to develop decision tools that support decision-makers in the construction industry in establishing strategic decisions.

Significant prior research has explored Construction 4.0 technologies and decision-making. Ref. [9] reviewed the state of digital twin (DT) development. As such, [9] suggested incorporating a multi-actor game-theory decision algorithm, optimizing scenarios for decision-making, developing resilience control, and utilizing decision-support tools. Next, [10] underwent a systematic review to identify research themes, gaps, and roadmaps for applying emerging technologies in industrialized construction. This review highlighted the need for a performance assessment for decision-makers to adopt Construction 4.0 technologies. Also, developing a comprehensive performance assessment is vital to persuade decision-makers to adopt advanced technologies. In another SLR article, [11] proposed a Construction 4.0 framework by identifying the enabling technologies and their applications. Ref. [11] identified that one of the significant scenarios is decision support for prefabricated construction. The article highlighted integrating AI and the IoT with building information modeling (BIM) to support prefabricated construction. In addition, [12] conducted a systematic review of Construction 4.0 technology adoption for off-site construction (OSC). According to [12], adopting Construction 4.0 for OSC could save time and costs, decrease waste, and enhance the overall productivity of projects. For OSC, five (5) key technologies are significant for establishing strategic and accurate decisions. These are BIM, global positioning systems (GPSs), the IoT, AI, and robotics. On the contrary, [13] presented ten new Construction 4.0 technologies in AEC using a scoping review. These consisted of BIM, AI, 3D printing, machine learning (ML), the IoT, geographic information systems (GISs), virtual reality (VR), big data, robotics, and AR. These technologies could assist in establishing sound decisions in the construction industry. In addition, [13] disclosed three (3) technologies that are currently adopted in the construction industry, including mobile devices, BIM, and digital signatures.

There has been a growing number of publications on Construction 4.0 technologies and decision-making in the construction industry. Nevertheless, the existing body of knowledge lacks an overview of research related to integrating Construction 4.0 technologies and decision-making. The existing literature often focuses on deciphering a more comprehensive piece of Construction 4.0 technologies. In contrast, this study has a narrower focus on Construction 4.0 technologies and decision-making. There is also a severe issue highlighted by the reluctance of construction professionals to implement Construction 4.0 in practice. Moreover, previous research identified that the decision-making efforts concerning technology selections are undeveloped [14]. The lack of information on Construction 4.0 technologies, their functions, and poor decision-making skills might lead to the reluctance issue. Also, to the authors' knowledge, there has been a grey area in Construction 4.0 technologies and decision-making despite its growing trends. Indeed, reviewing and understanding what was researched in the existing literature is necessary. This would persuade the decision-makers in the construction industry to establish the strategic decision to fully adopt the Construction 4.0 technologies. However, a comprehensive and systematic review to grasp the current knowledge gaps is lacking. Therefore, this study aims to review the publication trends in Construction 4.0 technologies and decision-making and pinpoint the gaps in the prior research. This study fills this knowledge gap by critically evaluating the state of Construction 4.0 technologies and decision-making, examining the trends, and pinpointing the existing gaps.

2. Literature Review

2.1. Construction 4.0 Technologies

Construction 4.0 adapts the IR 4.0 framework, comprising cyber-physical systems and advanced digital technologies in practice [15]. For example, in Malaysia, policymakers have established the Construction 4.0 strategic plan (2021–2025) as the roadmap for the next digital revolution in the local construction industry. This plan introduces twelve technologies to enhance construction competitiveness and productivity, including BIM, cloud and real-time collaboration; AI; blockchain; IoT; big data and predictive analytics; 3D scanning and photogrammetry; prefabrication and modular construction; AR and virtualization; 3D printing and AM; autonomous construction, and advanced building material. One significant Construction 4.0 technology that could enhance the efficiency of construction management is BIM. BIM is a simulation and modeling technology that synchronizes information with the client, consultant, and contractor [16]. Cloud and real-time collaborations are internet-centric, based on information resource storage [17]. On the contrary, AI technology is a simulation of human intelligence processes based on computer systems to conduct tasks through a set of algorithms [18]. Following that technology, blockchain refers to a distributed ledger of databases that comprise significant information, records of transactions, and internet protocols in a network of computers [19]. Meanwhile, the IoT refers to the sensor on devices that could track performance, optimize energy and improve the security and health parameters for construction players [5]. Furthermore, large amounts of construction project data are stored, managed, and processed for scientific decision-making, known as big data and predictive analytics [20]. Ref. [21] defines 3D scanning and photogrammetry as 3D data acquisition and mapping tools for detecting a thousand points per second to produce 3D photographs using the laser. Next is prefabrication and modular construction. It is a complete component of construction systems assembled in the factory before the final installation on site [17]. All these technologies are applied frequently across project phases and are in line with [5,6].

On the contrary, four Construction 4.0 technologies are adopted based on suitability and requirements, including AR and virtualization, 3D printing and AM, autonomous construction, and advanced building material. AR and virtualization revolve around human and computer interactions through wearable devices [18]. Moving on to 3D printing, AM creates a physical object modeled digitally [18]. Autonomous construction requires an intelligent machine or robot that transforms data into physical actions during construction, operation, and maintenance [22]. Finally, advanced building materials (i.e., high-performance concrete, aerogel, and foamed aluminum) are applied in the construction phase to upgrade the quality of constructed facilities [23]. These emerging technologies could increase productivity, improve collaboration, enhance sustainability, and tackle complex projects [22].

2.2. Decision-Making in Construction

Decision-making is choosing to solve problems from a set of alternatives based on rational, intuitive, or political processes [24]. In the construction business, the client, designer, project manager, supervisor, and contractor hold high responsibilities for establishing the decision [25]. During construction projects, decision-making skills are essential for a project manager for every step to avoid any severe delay in a project schedule [26]. Moreover, alternatives to rational and analytical thinking are critical for complex projects to ensure strategic decision-making to solve arising problems. Therefore, a holistic understanding of decision-making in project management is essential for all managers and other stakeholders involved. In the worst-case scenario, there is a high risk of the project slowing progress or stagnating completely if the decision-makers select the wrong decisions. The primary factor in achieving the project objectives is gathering the inputs from a group of decision-makers that initiated critical decision-making discussions in the early stages of construction projects [27]. As such, decision-makers need to find relevant and practical approaches.

Efficient decision-making means more efficient management of projects and opportunities to improve management methods to meet costs, fulfill needs (biological, physical, social, and organizational), and time management for construction work and schedules [28]. In addition, there are three major components for solving decision-making problems: decision-makers, decision tools, and techniques to select the best alternatives [29]. According to [29], the decision-maker's profile shifted from individual to hierarchy and networked decision-making. Regarding the decision tools, the parameter changed to the fuzzy format, while the techniques to select the best alternatives changed from judgmental to rational and axiomatic techniques. Ref. [30] reported the benefits of utilizing decision support tools that minimized the cost and time during the decision-making process in the public and private sectors. As the complexity of construction projects increases, thus, the profile of the decision-makers, parameters for the decision tools, and the techniques for selecting the best alternatives also change. Therefore, it is critical to ensure that construction professionals corroborate informed decisions in selecting Construction 4.0 technologies.

3. Materials and Methods

An informed and effective decision-making process for implementing Construction 4.0 technologies in construction organizations is crucial for project success. Therefore, this study systematically reviews Construction 4.0 technologies and decision-making. An SLR is a way to synthesize scientific evidence to answer a research question by assessing the published evidence in journals or articles on a selected topic [31]. A comprehensive SLR addresses the research questions by synthesizing published articles on a particular topic, identifying future research directions, and disclosing the research gaps [32]. Thus, an SLR is suitable for establishing an overview of Construction 4.0 technologies and decision-making, providing evidence-based insights on a research topic, and addressing the significant gaps. Additionally, this study applies the systematic method of the PRISMA protocol guidelines. According to [33], the PRISMA guidelines comprise a four-phased flow diagram based on: phase 1: identification, phase 2: screening, phase 3: eligibility, and phase 4: inclusion. The PRISMA method's transparency renders the methodology and analytical process more straightforward and precise [34]. Thus, it helps to produce evidence-based research and improves the quality of the review [35]. In addition, most construction research applied this method [36–38]. Figure 1 illustrates the SLR procedure.

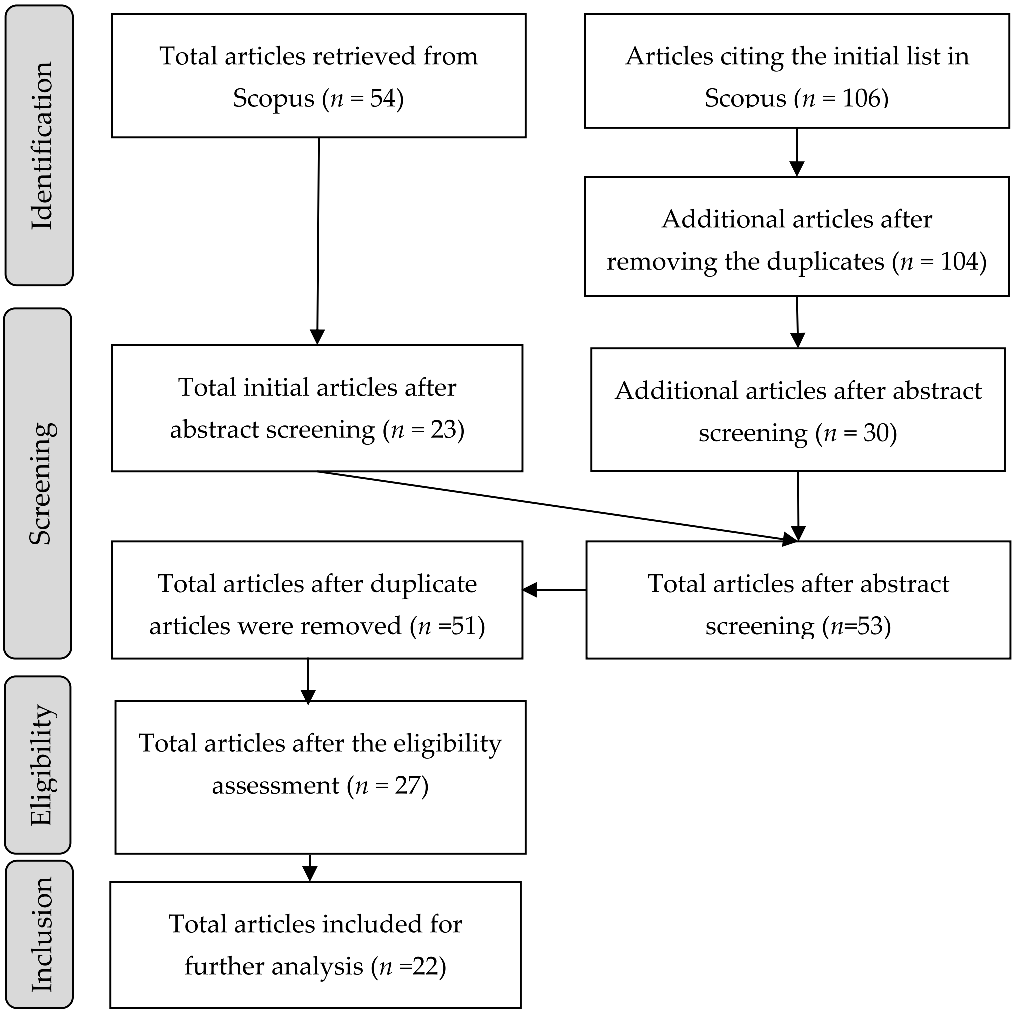

Figure 1. The systematic literature review procedure.

This study used the Scopus database to retrieve the articles for the SLR. Much prior research in construction and other fields (e.g., engineering, management, and business) used Scopus for SLRs as it has the largest abstract and citation databases [39,40]. This is true when compared with other databases, such as Google Scholar, Web of Science, and PubMed. Scopus offers the most comprehensive coverage of construction research [41]. Furthermore, since 2004, Scopus has covered 15,000 journals from 4000 publishers and is being reviewed annually to ensure that high-quality standards are maintained [42]. As the review involves a new and emerging topic that might result in fewer articles, this study used general keywords for the search, i.e., “Construction”, “4.0”, and “Decision”. In addition, the search was limited to journal articles in English. According to [43], the limitation of high-impact journal articles for review papers is significant to synthesize the existing research for a valuable overview of the knowledge and insights. Therefore, the search was limited to journal articles and excluded conference proceedings in order to provie a high-quality review synthesis. The search algorithm was: (TITLE-ABS-KEY (construction AND 4.0 AND decision)) AND (LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (SRCTYPE, ”j”)). The search resulted in only 54 journal articles.

As the search result was minimal, this study also included articles that cited the initial 54 articles to ensure the comprehensiveness of the review. A total of 106 articles that cited the 54 articles were retrieved from Scopus. Then, 2 articles with duplicates were removed, leaving 104 citing articles. In the screening phase, the articles’ abstracts were reviewed. As a result, 23 initial and 30 citing articles were selected. Two duplicate articles were removed when the initial and citing articles were combined. Then, the full articles were reviewed during the eligibility phase, resulting in 27 articles. Finally, five more articles were removed after examining the full content. In the end, 22 articles were valid for further analysis.

The number of identified articles was similar to other published SLRs stipulated for Construction 4.0 technologies. For example, in similar research by [44], out of 300 identified articles from the database, only 10 were relevant. Another example is by [7]; out of 547 identified articles, the research only included 20 for the final review. Moreover, [45] reviewed 27 articles out of 113 identified articles from Scopus. Meanwhile, [46] proposed a comprehensive multi-dimensional Construction 4.0 sustainability framework by systematically reviewing 29 out of 1007 articles from a Scopus search. Moreover, [47] reported that few publications exist in the current literature as “Construction 4.0” is still a new and emerging topic. Furthermore, as this study focused on Construction 4.0 technologies and decision-making, the topic is more specific and narrower than other prior reviews on Construction 4.0 technologies. Therefore, the sample size could be considered adequate to overview the current research trends in Construction 4.0 technologies and decision-making.

Thematic Analysis

Ref. [48] suggested an inductive approach to analyze the final list of articles during an SLR. A thematic analysis method is an inductive approach to identifying, analyzing, and reporting on the patterns or themes within a data set [48,49]. Therefore, a thematic analysis was used to define and evaluate patterns or themes from the final list of articles. In other words, the categories or names for the themes were unknown until after the data analysis.

4. Results

4.1. Overview of the Existing Research

Figure 2 depicts the selected journal articles annually for 15 years, from 2007 to 2022. The publication year for scientific research on decision-making and Construction 4.0 technologies starts in 2020, with most publications published in 2022. Out of 22 articles, 11 of them were published in 2022 (50%), 7 in 2021 (32%), and 4 in the year 2020 (18%). Although the number of relevant publications covering these topics was limited, the article number indicated a rapid development, as the number of articles grew tremendously until 2022. These results show that this topic has been gaining attention in recent years by researchers, probably as a vital strategy for the construction industry to recover from the COVID-19 disruption that adversely impacted this industry. According to [50], labor scarcity, supply chain disruption, decreased construction productivity, increased project financing rejection rates, and reduced foreign investments are among the critical pandemic impacts on the construction industry.

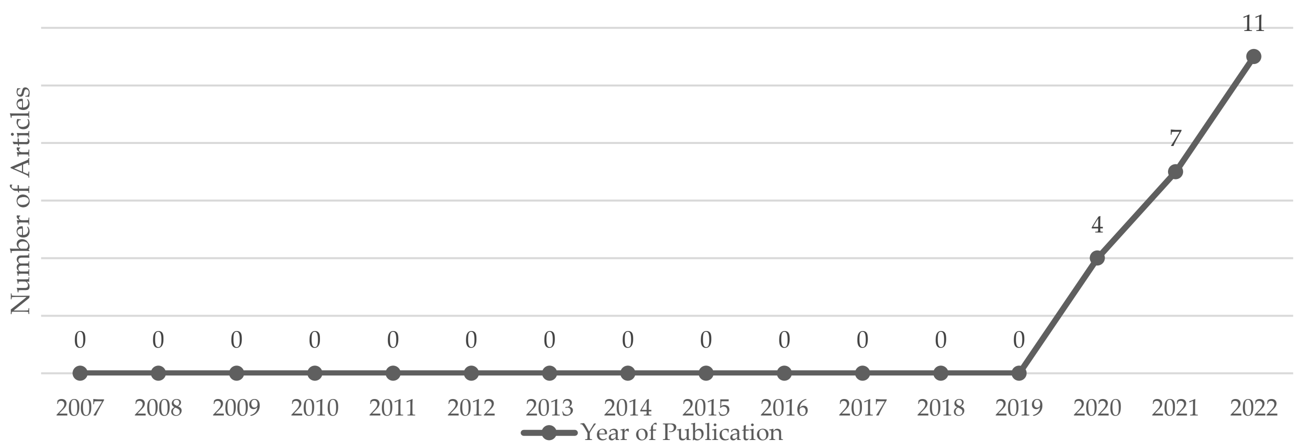

Figure 2. Publication years of the reviewed articles.

Table 1 presents a summary of the publications from the SLR. The Journal of Engineering, Design, and Technology and Buildings published the most articles compared with the other journals. The listed journals in Table 1 show that various journals actively publish research-based topics. Therefore, it proves the growing interest in this area of research and this study on the current trends in the construction industry as it started to grow in 2020.

Table 1. Journal titles of the reviewed articles.

Journal Title	No. of Articles	Source
Journal of Engineering, Design, and Technology	2	[51,52]
Built Environment Project and Asset Management	1	[53]
Innovative and Sustainable Built Environment	1	[54]
Production Planning and Control	1	[55]
Journal of Computing in Civil Engineering	1	[56]
Engineering, Construction, and Architectural Management	1	[57]
International Journal of Environmental Research and Public Health	1	[58]
Sustainability (Switzerland)	1	[59]
Journal of Engineering, Project, and Production Management	1	[60]
Journal of Construction Engineering and Management	1	[61]
Journal of Management in Engineering	1	[62]
Journal of Architectural Engineering	1	[63]
International Journal of Construction Management	1	[64]
Buildings	2	[65,66]
Malaysian Construction Research Journal	1	[67]
Environment, Development, and Sustainability	1	[68]
Infrastructures	1	[69]
Environmental Science and Pollution Research	1	[70]
Journal of Civil Engineering and Management	1	[71]

4.2. Thematic Analysis

In this study, the thematic analysis of the final list of articles resulted in the following main themes: strengths, weaknesses, opportunities, and threats. Each theme has several subthemes, as illustrated in Figure 3. The subsequent subsections discuss the theme and subthemes.

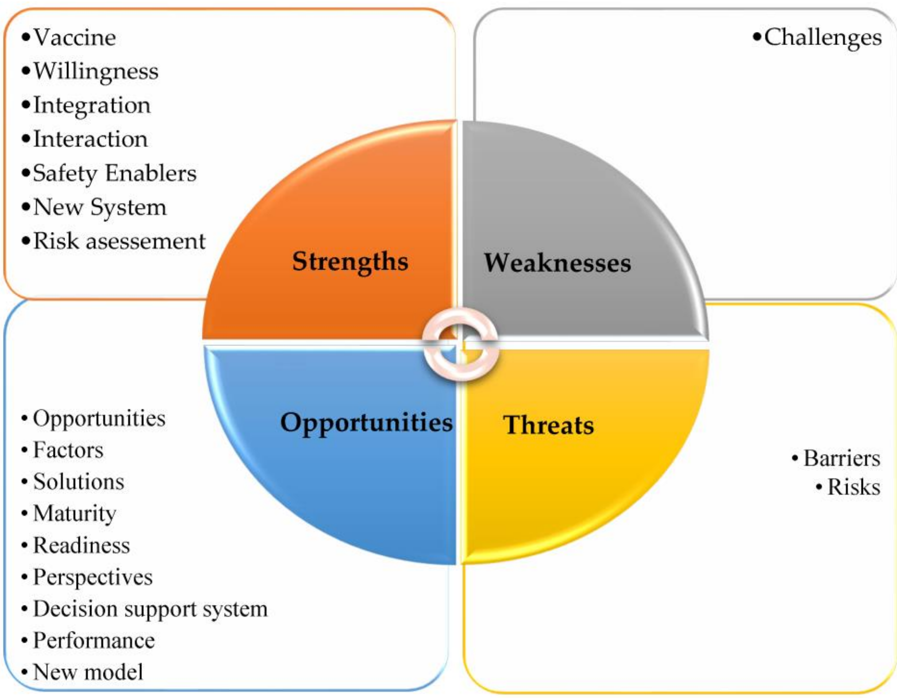

Figure 3. Themes and subthemes for the existing research on Construction 4.0 technologies and decision-making.

4.2.1. Strengths

Strengths are the positive attributes of the internal environment to achieve the anticipated organizational objectives. This study's seven articles (28%) contributed to seven subthemes. The subthemes are vaccine, willingness, integration, interaction, safety enablers, new system, and risk assessment.

The suspension of construction activities during the COVID-19 pandemic adversely impacted the construction supply chain management. Due to the movement control order (MCO), most construction activities were forced to stop operating. As such, [52] disclosed Construction 4.0 technologies as the effective vaccine for better decision-making during the COVID-19 pandemic. Therefore, most construction professionals are highly willing to adopt Construction 4.0 technologies for the resiliency of supply chain management. This includes an intelligent construction site, simulation tools, and virtualization for facilitating decision-making. These technologies could enhance the design, management, operation, and adequate decision-making of construction projects. As such, the framework for applying Construction 4.0 technologies was proposed by [53] to improve project performance. Moreover, integrating Construction 4.0 technologies on the same platform is vital to produce high-quality construction outputs throughout the project's life cycle. Ref. [54] validated that integrating deep learning and the DT has a high potential to support efficient decision-making through cognitive abilities. Workers or machines work with low capacities, and poor production schedules are the reason for low construction productivity. Ref. [55] developed a lean construction (LC) and BIM interaction model to increase production. This model assisted decision-makers in determining significant LC and BIM parameters to achieve the organizational objectives and project success.

Construction safety is crucial to avoid accidents, fatalities, injuries, and disease due to the industrial nature of work dealing with risky activities. Ref. [51] discovered that BIM, wearable safety technologies, and robotic and automation technology (RAT) are significant for safety management. These safety enablers could enhance hazard identification, reinforce safety planning and decisions on the appropriate safety measures, improve safety inspections, monitoring and supervision, and increase safety awareness. Recently, virtual assistants, such as Apple's Siri and Google Assistant, are growing in popularity among users. Thus, [56] developed a new system in the form of query-answering (QA) for BIM information extraction (IE) in the construction industry to assist decision-making. This system served as a virtual assistant for construction professionals to establish decisions based on accurate information using BIM. The construction industry is not immune to unintended outcomes and distractions of Construction 4.0 technologies such as blockchains. Ref. [57] proposed a novel model for risk assessment to assist the construction professional in data-driven decision-making to manage blockchain risks.

4.2.2. Weaknesses

Weaknesses relate to negative attributes that are harmful to achieve organizational objectives. There are three articles (12%) in this theme and a subtheme, which includes challenges.

The construction industry is constantly experiencing poor health and safety performance resulting in injuries, fatalities, and accidents. Hence, [58] focused on increasing awareness among decision-makers to establish safer decisions by utilizing Construction 4.0 technologies in construction management. The safety technologies were the IoT, radio frequency identification (RFID), VR, sensors, drones, and BIM. However, implementing these technologies was challenged by a lack of relevant skills, low training capacities, pricy technologies, and negative perceptions, for example, the fear of job loss by industry professionals. Usually, on construction sites, IoT technologies are used by the project managers and construction personnel to create reports, on-site monitoring for material and labor needs, and other necessary site details. Hence, [59] created a model relationship between the different challenges of IoT implementation to establish informed decisions for construction professionals. This model could assist in handling and delivering efficient project performance. The significant challenges for implementing IoT are technical and extensive data management. Apart from construction project management, organizational management plays a significant role in the digital transformation of the construction industry. However, it has not been explored. Therefore, [60] aimed to foster the implementation of Construction 4.0 technologies by identifying organizational challenges. The known challenges could assist the top and lower management in formulating strategies and deciding on digital innovations. Digital transformation in the construction industry primarily depends on management and strategic challenges. Undoubtedly, identifying organizational challenges in human resources and society, organizational factors, management, and financial and customer satisfaction are significant.

4.2.3. Opportunities

Opportunities are the favorable external factors in an organization that is exploitable for their advantages. It is essential to realize that most of the published articles in the decision-making and Construction 4.0 area were considered opportunities. A total of 12 articles (48%) demonstrated 9 subthemes, including opportunities, factors, solutions, maturity, readiness, perspectives, decision support system, performance, and a new model.

Construction 4.0 technologies are crucial to improving the health and safety performance of construction sites. In that case, [58] emphasized the opportunities of Construction 4.0 technologies that could suggest safer decisions for workers. It could enhance workflow, safety inspections, information management, and accountability. Despite being the most crucial driver for digital transformation, RAT has limited application in the construction industry. Given this issue, [61] identified the positive and negative factors that could impact the decisions of construction organizations to adopt RAT. Based on the empirical results, cost factors (e.g., the initial costs and long-term cost savings) positively and negatively impacted the application of RAT. In line with this article, [62] assessed the benefits and barrier factors for decision-makers to decide on implementing RAT based on multi-stakeholder perspectives. The findings highlighted RAT's more focused, efficient, and user-friendly improvements.

Most of the research cited the limitation of Construction 4.0 technologies application in the construction industry due to cost factors. Hence, [59] recommended a digitalized cost analysis to reduce the implementation risks and support the decision process for organizational management. Adopting Construction 4.0 technologies in industrialized construction enhanced the off-site construction process and project delivery. Then, [63] developed a maturity framework to help organizations establish data-driven and fast decisions for adopting Construction 4.0 technologies. In the meantime, organizational readiness is a crucial element of industrialized construction maturity. Thus, to establish a better decision to adopt industrialized construction, organizations need to assess their readiness and encourage a culture of readiness. It includes readiness for change, accepting innovations, and professional development [63]. The maturity framework classified emerging technologies into four categories. These include business digitalization, computer-integrated design, data acquisition, optimization, predictive analytics, and RAT. These technologies are significant in improving the off-site construction process. Moreover, there are four levels of maturity: explore, initiate, control, and optimize. This framework provides practical recommendations for shifting an organization's operational model from conventional to industrialized construction.

Different from [63,64] proposed a multi-criteria decision-making model named ConFIRM. This model has the function of measuring the strategic readiness of construction firms concerning Industry 4.0 technologies' implementation. The results showed that human capital components (e.g., intellectual agility, knowledge, skills, and competencies) are the most critical success factors for implementing Construction 4.0 technologies. Using the ConFIRM model, the management team could establish fast and informed decisions to determine whether their organization is suitable to adopt Construction 4.0 technologies. Moreover, this model assists in acquiring some intellectual capital and recommends action plans to establish better judgments in adopting Construction 4.0 technologies. Industrialized construction is a system that uses innovation in design by employing intelligent manufacturing and automation. It is known as off-site construction, prefabrication construction, or modular construction. This system benefitted the industry by reducing construction costs, time, and labour. Despite the compelling benefits of industrialized construction, there is a lack of research that reveals the Construction 4.0 technologies' developmental potential, benefits, and potential barriers. As such, [65] provided an in-depth understanding of industry practitioners' attitudes to adopting emerging technologies in industrialized construction. From the US practitioners' perspective, 3D and nD models, sensing techniques, and business information models are the technologies with the highest current utilization. On the contrary, extended reality, AM, and advanced data analytics are the technologies with the highest developmental potential. Project inputs (e.g., cost, time, and labor), implementation costs, software constraints (e.g., capital costs and software upgrading), and compatibility are the main factors for technological adoption. Inter-group comparison results indicated that the organizational background has a marginal influence on practitioners' perspectives. In contrast, personal career profiles could significantly affect practitioners' perspectives.

In developing countries, the lack of awareness and resistance to change has hindered digital innovation in the construction industry. Thus, [67] assessed organizations' decisions for digital transformation through BIM implementation in developing countries. The results revealed that the digital transformation journey through BIM implementation in this country is already in place and practiced. However, for successful digitalization, it requires a mindset change toward cultural, organizational, and operational transformation. Also, it needs an innovative integration of emerging technologies, processes, and competencies across the construction life cycle. Unfortunately, most construction organizations focus on BIM adoption and ignore other Construction 4.0 technologies. As such, [72] developed a technological adoption decision-making framework for decision-makers. Based on the technology acceptance model (TAM) and the expectation confirmation model (ECM), it allows the decision-makers to adopt multiple Construction 4.0 technologies. The TAM is the theory that measures users' attitudes to using new technology at a single point at one time. In addition, it has two specific measurements: perceived ease of use and usefulness. On the contrary, the ECM refers to the theory that measures satisfaction and dissatisfaction when using technologies or existing technologies' performance after using them. In that research, the author used the TAM and ECM theories and provided critical steps for the final decision of organizations up to the commencement of the technological operation. This research identified that the managers at the top, middle, and production levels are the primary decision-makers in adopting technologies in construction organizations. Usually, they decide on a discussion regarding technology and finances.

Supply chain management is critical in the construction industry to achieve project success, especially in project-oriented organizations. Construction organizations may face project risks without suitable performance suppliers, including cost overruns, improper quality, and delivery delays. In addition, PESTEL (political, economic, social, technological, environmental, and legal) risks could disrupt the construction supply chain. In recent years, COVID-19 struck the whole world's economy and adversely impacted the construction supply chain and productivity. Post-COVID-19 research in [68] proposed a novel approach to assist decision-making in choosing a high-performance supplier. This approach was based on three aspects: localization, agility, and digitalization for a resilient construction ecosystem. The findings showed that the most critical criterion for construction supplier performance measurement was "digitalization". Adopting Construction 4.0 technologies, such as big data, IoT, advanced robotics, and distributed ledger technology (DLT), could help suppliers establish proactive strategies and run predictive analytics. With digitalization, suppliers could expand networking and automate every process for operational effectiveness. Also, it could enhance customer satisfaction and rapidly recover from supply chain disruptions.

Transportation management is part of supply chain management that is crucial for controlling the delivery flow of materials, tools, and equipment for installation at construction projects. Heavy machinery, such as trucks, are traditionally one of the highest costs to consider, mainly due to fuel consumption. However, until now, an accurate estimation of fuel consumption for this transport machine has been absent, resulting in an uncontrolled and untraced actual cost spent on transportation. Taking account of this issue, [69] proposed a fuel consumption estimation model for decision-makers to properly manage construction resources (e.g., economic and physical). This model functions to prepare for unpredictable occurrences (e.g., equipment malfunction and low productivity). The results revealed that fuel consumption strongly correlated with cargo, route inclination, and total distance. Furthermore, it proved that these criteria are key input parameters for achieving accurate and reliable fuel consumption predictions. As the prediction model combines sensor and ML algorithms, it demonstrated its viability in real-world construction.

4.2.4. Threats

Threats are potential risks from external factors that could jeopardize the organizational goal. For this study, three articles (12%) were categorized under threats with subthemes of barriers and risks.

DLT, or the blockchain, is a powerful business enhancer whose potential could disrupt the construction industry's project delivery and business model. However, due to several barriers and challenges, this technology has not reached the plateau of productivity. Therefore, [70] evaluated the applicability of identified challenges and barriers based on a sustainability perspective for the construction organizations to decide on adopting DLT. There are 41 barriers parked under four categories: project level, organizational level, market/industry level, and construction ecosystem level. The infrastructure for data management is the top-ranked barrier at the project level. While at the organizational level, the lack of advanced applications and archetypes is the highest barrier. On the contrary, a lack of customer demand hinders DLT adoption in the construction industry. Lastly, DLT needs further improvement in taxation and reporting in the construction ecosystem. In this case, the findings revealed that the barriers to DLT affected social sustainability, followed by economic, environmental, and project sustainability.

The adoption rate of Construction 4.0 technologies is relatively low, especially in managing occupational safety and health (OSH) risks. Amongst other industries, the construction industry has the slowest uptake for digital transformation. In developing countries, barriers to implementing these safety sciences and management technologies are under research. The barriers could negatively impact construction workplace safety, increase risks, and reduce productivity in hazardous construction sites. To help address this situation, [61] explored the critical barriers for construction professionals to decide on adopting new safety sciences and management technologies. The critical barriers were the investment costs for new technologies, the construction industry's culture, incompatible client needs, the resistance to change among construction professionals, and a lack of top management and leadership support.

Apart from barriers, risk identification for adopting and implementing Construction 4.0 technologies in the construction industry is urgently required. Therefore, researchers and construction professionals should investigate possible risks that could influence the benefits of technology implementation in the construction industry. As a result, it could increase stakeholders' willingness to use these technologies. The impacts of these risk factors vary according to the technologies' type and function. For example, immersive technology (ImT), such as VR, AR, and mixed reality, would bring value to the construction industry by enhancing project communication, training workers, and assisting project coordination. They integrate physical and virtual environments that allow the users to experience blended reality. Five risk categories were identified by [66] to guide the practitioner in adopting and integrating ImT for construction projects. These were technology concerns, operational limitations, investment limitations, individual concerns, and external issues. High investment costs (investment limitations), the need for extensive worker training (individual concerns), and the possibility of introducing new risks to workers (individual concerns) were among the significant risk factors for ImT technology. Moreover, the research also modeled three statistically significant hypothesized risk paths: external issues and individual concerns, external issues and investment limitations, and individual and technology concerns.

5. Discussion

5.1. Characteristics of the Existing Research

Based on the results, this study synthesizes the knowledge gaps in the existing research on Construction 4.0 technologies and decision-making. Table 2 presents the characteristics of the articles. There are four themes, with seven articles under strengths, twelve under opportunities, and three under weaknesses and threats. It could be induced that strengths and opportunities would drive the research in Construction 4.0 technologies and decision-making. The probable reason could be that these themes could help achieve a total digital transformation in the construction industry. It is in line with [73]'s review of Construction 4.0 research. Ref. [73] recorded a rapid increase in publications from 2014 to 2019, contributing to a 283% growth rate. Nevertheless, the integration of Construction 4.0 technologies and decision-making is currently less explored by existing research. On the contrary, construction organizations should investigate the weaknesses and threats that are harmful and unfavorable in accomplishing Construction 4.0. Low-skilled workers are the crucial threats to construction 4.0 successful adoption [74]. Inadequate training for construction professionals resulted in a moderate knowledge level to adopt and run the construction 4.0 technologies. Thus, it could harm internal management since investments for the technologies are made but cannot be operated due to weak human capital. Therefore, it is crucial to have effective leadership in Construction 4.0 to face that critical challenge [75]. Additionally, both themes could serve as the lessons learned to strategize actions.

Meanwhile, the most highlighted area amongst the reviewed articles is the key factors, followed by the decision process, integrated technologies, one technology, and a decision support tool. The key factors included challenges, barriers, and solutions for the implementation of Construction 4.0 technologies in construction projects and organizations [58–60,70,71]. At the same time, [61,65] highlighted the factors for implementing Construction 4.0 technologies [61,65]. Meanwhile, [66] identified the critical risk factors for successfully implementing Construction 4.0 technologies. In summary, most previous research focuses on adopting and implementing Construction 4.0 technologies.

Even though there is research on the decision support system for Construction 4.0 technologies, the researcher proposed a decision-making model based on the strategic readiness of the construction organizations [64]. On the contrary, [75] developed a technological adoption decision-making framework. The developed framework aimed to guide decision-makers in adopting Construction 4.0 technologies in organizations. However, if construction organizations are unaware of the available emerging technologies, adopting technologies would focus on one or two known technologies, as the research conducted by [56,57,69] emphasized the use of one specific technology. Integrating multiple technologies has more potential than fragmented applications in establishing a cyber-physical system to enhance the overall capabilities of construction organizations [76]. Ref. [77] presented eight technologies that implemented IoT mechanisms for Construction 4.0 preparation: BIMs, smart communication, big data, sensors, RFID, AR, remote operations, and GPSs. As such, a few existing research articles explored the integrated emerging technologies for safety areas [51], the integration of deep learning and DT [54], lean and BIM [55], and supplier performance measurement [68]. Other than that, there is some research on decision-making in implementing Construction 4.0 technologies [52,53,63,67]. In summary, research in Construction 4.0 technologies and decision-making is growing. However, the existing research focused on adopting and implementing Construction 4.0 technologies rather than integrating technologies and decision-making processes.

Table 2. Characteristics of the reviewed articles.

Source	Purpose	Area	Subtheme	Theme
[52]	Modeling technologies	Decision process	Vaccine	Strength
[53]	Adoption technologies	Decision process	Willingness	
[54]	Investigation technologies	Integrated technologies	Integration	
[55]	Synergy	Integrated technologies	Interaction	
[51]	Adoption technologies	Integrated technologies	Safety enablers	
[56]	Virtual systems	One technology	New system	
[57]	Management frameworks	One technology	Risk assessment	
[58]	Implementation technologies	Key factor	Challenges	Weaknesses
[59]	Implementation technologies	Key factor	Challenges	
[60]	Implementation technologies	Key factor	Challenges	
[58]	Implementation technologies	Key factor	Opportunities	Opportunities
[61]	Adoption technologies	Key factor	Factors	
[62]	Adoption technologies	Key factor	Factors	
[59]	Implementation technologies	Key factor	Solutions	
[63]	Adoption technologies	Decision process	Maturity	
[63]	Adoption technologies	Decision process	Readiness	
[64]	Implementation technologies	Decision support tool	Readiness	
[65]	Adoption technologies	Key factor	Perspectives	
[67]	Implementation technologies	Decision process	Decision	
[72]	Implementation technologies	Decision support tool	Decision	
[68]	Criteria measurement	Integrated technologies	Performance	
[69]	Implementation technologies	One technology	Prediction	
[70]	Adoption technologies	Key factor	Barriers	Threats
[71]	Adoption technologies	Key factor	Risk	
[66]	Adoption technologies	Key factor	Barriers	

5.2. Existing Research Areas, Limitations, and Future Research Directions

This SLR also disclosed the limitations and future directions of the existing research on Construction 4.0 technologies and decision-making. However, these limitations and suggestions are compiled from the reviewed articles. Therefore, future explorations are not limited to the findings. Table 3 shows that most research has limitations in their methodologies, which include using a single research strategy, either qualitative or quantitative, and cross-sectional methods [52,63–65]. Therefore, future research could validate prior findings using other research strategies, longitudinal studies, or using other decision-making theories [57,68,70,75].

Furthermore, most of the data collection for the reviewed articles was limited to one country with a small sampling size [53,58,63,65,75]. Consequently, the findings could not be generalized to represent the whole target population in the construction domain [69,75]. To establish more reliable and generalizable data, [52] proposed to conduct further research in other developing countries and increase the sample size [51,57,58,62,65]. At the same time, [55] recommended testing the performance of the developed model and framework with an additional expert with a different project nature. Moreover, most articles focused on a single Construction 4.0 technology [51,61,65,66,69]. This situation shows that the decision to adopt Construction 4.0 technologies is still limited and fragmented [51]. To counter these issues, [53] proposed increasing the awareness of applying Construction 4.0 technologies through seminars or workshops. While [51,65] suggested industry-academia collaboration efforts in exploring the true potential of Construction 4.0 technologies.

Table 3. The link between the existing research, research limitations, and future research directions.

Theme	Subtheme	Research Limitation	Future Research Direction
Strength	• Vaccine • Willingness • Integration • Risk Assessment • Safety Enablers • Interaction • New System	• No triangulation between quantitative and qualitative data • Limited to one country • The application of Construction 4.0 technology is still limited and fragmented. • Limited research in developing countries • Small sampling size	• Adoption of Construction 4.0 technologies for the resiliency of the construction industry • Integration of Construction 4.0 technologies and supply chain • Construction 4.0 technologies in developing countries • Strategies for improving awareness of Construction 4.0 technologies. • Strategies for introducing Construction 4.0 technologies at the tertiary level • Risk assessment models for Construction 4.0 technologies at the project, organization, market, and supply chain levels (e.g., grey OPA, original OPA, opportunities, and threats) • Strategies for responding to risks associated with Construction 4.0 technologies • Usage and barriers of Construction 4.0 technologies in construction safety • Enhancement strategies for industry-academia collaborations on Construction 4.0 technologies • Integration of Construction 4.0 technologies and DT at all project stages • Mapping the mechanisms for the real-time analysis of Construction 4.0 technologies' physical and virtual data • System structures and workflows of Construction 4.0 technologies in automating real-time decision-making • The categorization of Construction 4.0 technologies based on project suitability • The validation of the existing findings on Construction 4.0 technologies using another research strategy (e.g., industry experts or other projects)
Weaknesses	• Challenges	• Limited to one country • Limited to one Construction 4.0 technology	• The identification of social and technical factors for Construction 4.0 technology adoption in organizations • The development of Construction 4.0 guidelines using information from other industries • Challenges and solutions for implementing Construction 4.0 technologies throughout the construction value chain • Strategies for supporting Construction 4.0 implementation in organizations (e.g., decentralizing decision-making processes and rethinking digital transformation according to organizational hierarchy) • Technicalities and complexity of implementing Construction 4.0 technologies • Strategies for protecting against unauthorized access for facilities and management

Table 3. *Cont.*

Theme	Subtheme	Research Limitation	Future Research Direction
Opportunities	• Opportunities • Factors • Solutions • Maturity • Readiness • Perspectives • Decision support system • Performance • New model	• Limited to one country • Small sampling size • Lack of data sharing from respondents • No triangulation between quantitative and qualitative data • Lack of case studies. • Respondents have a limited understanding of Construction 4.0 technologies • Organizations lack policy on Construction 4.0 technology adoption	• Return on investment and cost-effectiveness of Construction 4.0 technologies • Risk and safety analysis to predict accidents and device malfunctions • Factors for resistance to adopting Construction 4.0 technologies • Integration between industrialized construction and Construction 4.0 technologies (e.g., extended reality, AM, and advanced data analytics) • The evaluation of developed Construction 4.0 systems using cost, time, labor, and quality indicators • Information interoperability between Construction 4.0 technologies • Applications to enhance the working efficacy of managers or developers using Construction 4.0 technologies • Relationships between Construction 4.0 technology utilization, organizational background, and individual profiles • The usage of other decision-making theories in Construction 4.0 technologies • The capabilities of suppliers to ensure the supply chain resilience of Construction 4.0 technologies • The validation of existing research findings (e.g., global data, different research strategies, stakeholders, case studies, and increased sample size)
Threats	• Barriers • Risks	• Pandemic COVID-19 restrictions • Long duration for data collection • Lack of data due to private and confidential information • No triangulation between quantitative and qualitative data • Small sampling size • Limited to one country • Limitations related to using surveys • Limitations related to using non-probability sampling	• The usage of other decision-making theories in Construction 4.0 technologies (e.g., OPA-F) • The development of decision-making processes and frameworks using alternative decision-making theories (e.g., OPA) • The synergy between the challenges and benefits of Construction 4.0 technologies • The validation of existing research findings (e.g., global data, different research strategies, stakeholders, case studies, and increased sample size)

The cost factor or investment factor in the acquisition, operation, and maintenance of a technology type is a critical factor that hinders the adoption of Construction 4.0 technologies among organizations [61]. There are four suggestions to counter this cost issue. First, undergo financial analysis such as the return on investment [61]. Second, to offer subsidies on acquisition costs [53]. Third, to establish government tax relief and incentives for organizations that adopt Construction 4.0 technologies [62]. Fourth, to present information on cost-effective technology types [65]. Ref. [65] suggested evaluating the developed framework or model for adopting Construction 4.0 technologies using cost, time, labor, and quality. The weak topic gave the drawback of input. Thus, the existing scope of research is limited to Construction 4.0 challenges for construction projects, management, and organization. Henceforth, moving forward, [58] advised construction professionals to follow and adapt guidelines from other industries (e.g., manufacturing) to assist decision-making in adopting Construction 4.0 technologies. In addition, digital transformation in organizations should be rethought, such as introducing decentralized decision-making and investigating the complexity and technicality of digital innovation.

Despite the opportunities to adopt Construction 4.0 technologies in organizations that could bring benefits, the implementation of Construction 4.0 technologies is still very low. Nevertheless, the amount of research on Construction 4.0 technologies is growing exponentially in this era. However, limited research is still available on Construction 4.0 technologies and decision-making.

6. Conclusions

This study aims to review the publication trends in Construction 4.0 technologies and decision-making and pinpoint the gaps in the prior research. A total of 22 journal articles were carefully reviewed based on the PRISMA method and analyzed using thematic analysis. The analysis categorized the articles into four themes: strengths, weaknesses, opportunities, and threats. Additionally, the articles contributed to nineteen different subthemes: vaccine, willingness, integration, interaction, safety enablers, new system, risk assessment, challenges, opportunities, factors, solutions, maturity, readiness, perspectives, decision support system, performance, new model, barriers, and risks. The review suggests a knowledge gap in integrating Construction 4.0 technologies and decision-making. Most research focused on implementing Construction 4.0 technologies rather than providing an effective decision process.

This study is the first to conduct an SLR of research trends on Construction 4.0 technologies and decision-making. The study delves into the scientific trends and article classifications and pinpoints the research limitations, knowledge gaps, and future research directions for Construction 4.0 technologies and decision-making. Despite great efforts, this study still has a few limitations. First, the review focuses on the trends of Construction 4.0 technologies and decision-making only. Therefore, this study cannot represent other research areas related to Construction 4.0. The second limitation is that the literature search was conducted using Scopus. Hence, some articles indexed by other databases might be excluded. Nevertheless, the selected database is commonly used by construction and other research for SLRs, and therefore the methodology is acceptable. Another minor limitation is that all reviewed articles are in English. Regardless of these limitations, the aim of the study was adequately met.

The theoretical implication of this study is to provide insights into what has been explored in Construction 4.0 technologies and decision-making. These insights could prevent future researchers from conducting and developing similar research. Future researchers could use the study findings to identify existing research gaps before conducting research. Also, researchers could use the findings on the study limitations and future directions as a guide. Regarding the practical implications, industry practitioners could refer to the study findings when implementing Construction 4.0 technologies. In conclusion, this study provides both theoretical and practical implications.

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