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RESEARCH ARTICLE

Construction 4.0 technology evaluation using fuzzy TOPSIS: comparison between sustainability and resiliency, well-being, productivity, safety, and integrity

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Abstract
This study aims to compare the impact of Construction 4.0 technologies on different organizational core values, focusing on sustainability and resiliency, well-being, productivity, safety, and integrity. To achieve that aim, the study objectives are the following: (i) identify the critical Construction 4.0 technologies between core values; (ii) appraise overlapping critical Construction 4.0 technologies between core values; (iii) examine the ranking performance of Construction 4.0 technologies between core values; and (iv) analyze the interrelationships between Construction 4.0 technologies and core values. First, twelve Construction 4.0 technologies were identified from a national strategic plan. Then, the fuzzy technique for order of preference by similarity to ideal solution (TOPSIS) that incorporates subjective and objective weights was used to evaluate the impact of the Construction 4.0 technologies on the five core values. Finally, the collected data was analyzed using the following techniques: fuzzy TOPSIS, normalization, overlap analysis, agreement analysis, sensitivity analysis, ranking comparison, and Spearman correlation. The study findings reveal four critical Construction 4.0 technologies that enhance all five core values: building information modeling (BIM), Internet of Things (IoT), big data and predictive analytics, and autonomous construction. Also, there is a high agreement on the Construction 4.0 technologies that enhance well-being and productivity. Lastly, artificial intelligence (AI) has the highest number of very strong relationships among the core values. The originality of this paper lies in its comprehensive comparison of the impact of Construction 4.0 technologies on multiple organizational core values. The study findings provide valuable insights in making strategic decisions in adopting Construction 4.0 technologies.

Keywords Construction 4.0 · Decision-making · Fuzzy TOPSIS · Sustainability and resiliency · Well-being · Productivity · Safety · Integrity

Introduction

The construction industry is a cornerstone of the global economy and is undergoing a significant digital transformation (João Ribeirinho et al., 2020). This digital transformation is driven by the advent of Construction 4.0 technologies that reshape the organizational core values paradigm (Glass et al. 2022). Construction 4.0, stemming from the Fourth Industrial Revolution (IR 4.0), integrates digital technologies, analytics, and automation into construction projects (Osunsanmi et al. 2022). The discourse of Construction 4.0 navigates through the pivotal dimensions of sustainability and resiliency, acknowledging their importance in the face of contemporary environmental challenges (Maqbool et al. 2022). Furthermore, incorporating a broader spectrum of organizational core values such as well-being, productivity, safety, and integrity fosters a holistic understanding of the impact of Construction 4.0 technologies on different core values. Therefore, the advent of Construction 4.0 technologies is not only propelling the construction industry toward digitalization but also redefining its core values to

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encompass sustainability and resiliency, well-being, productivity, safety, and integrity.

Organizations rely on core values as guiding principles for success and growth (Elias et al. 2023). Failing to adopt Construction 4.0 technologies results in missed opportunities to achieve organizational core values, including sustainability and resiliency, well-being, productivity, safety, and integrity (Osunsanmi et al. 2020). For instance, construction projects without building information modeling (BIM) have lower productivity due to a lack of information, leading to inaccurate decisions and ineffective communication between stakeholders (Gurgun et al. 2022). Likewise, neglecting autonomous construction adoption lowers productivity and safety as workers endure hazardous and challenging environments (García de Soto et al. 2022). Similarly, not adopting the Internet of Things (IoT) leads to missed opportunities for enhancing safety, productivity, communication, and information management (Oke et al. 2022). Therefore, adopting Construction 4.0 technologies is crucial to avoid built environment organizations missing opportunities to achieve their core values.

Making strategic decisions in adopting Construction 4.0 technologies is crucial to align organizations toward achieving desired organizational core values. However, many organizations lack clear plans and long-term roadmaps, often leading to delayed or absent adoption of Construction 4.0 technologies (Magalhaes et al. 2023). This vagueness breeds ambiguity and resistance to change, pushing organizations to opt for older technologies, including IR 1.0 to IR 3.0, for cost-cutting measures. Additionally, short-term financial gains often divert funds away from Construction 4.0 technology investments (Nagy et al. 2021). Apart from cost, organizations are also inflexible in allocating adequate resources and information technology (IT) infrastructure for adopting Construction 4.0 technologies (Lokuge et al. 2019). Additionally, innovation without aligning technologies with core values leaves organizations unable to leverage competitiveness and unique selling propositions, resulting in lost business opportunities. Hence, making informed decisions when selecting Construction 4.0 technologies is vital.

Well-informed decisions are crucial for adopting Construction 4.0 technologies successfully in organizations. However, organizations frequently face difficulty making well-informed decisions due to the lack of information on the Construction 4.0 technologies (Shafei et al. 2022). A comprehensive understanding of the different impacts of Construction 4.0 technologies enables more effective decision-making within the organization. Specifically, comparing the impact of Construction 4.0 technologies helps organizations make informed decisions during selection. A lateral comparison provides objective and unbiased information on the impact of Construction 4.0 technologies on organizational core values. Moreover, such comparison fosters information for aligning Construction 4.0 and organizational core values. Also, decision-makers may establish clear benchmarking to evaluate different Construction 4.0 technology options based on specific targeted organizational core values. Furthermore, the imperative of informed decision-making demands approaches that use mathematical models for making better judgments (Al Mohamed et al. 2023). For example, strategically integrating multi-criteria decision-making (MCDM) into the approaches can guide decision-makers toward choosing the best alternatives (Basílio et al. 2022). Therefore, comparing the impacts of Construction 4.0 technologies on different core values assists organizations in making well-informed decisions in technology selection.

Given the above situation, this study aims to compare the impact of Construction 4.0 technologies on different organizational core values, focusing on sustainability and resiliency, well-being, productivity, safety, and integrity. To achieve that aim, the study objectives are the following: (i) identify the critical Construction 4.0 technologies between core values; (ii) appraise overlapping critical Construction 4.0 technologies between core values; (iii) examine the ranking performance of Construction 4.0 technologies between core values; and (iv) analyze the interrelationships between Construction 4.0 technologies and core values. These objectives are achieved through an MCDM method known as a fuzzy technique for order of preference by similarity to the ideal solution (fuzzy TOPSIS) that involves a three-phase methodology. First, the criteria (i.e., organizational core values) and alternatives (i.e., Construction 4.0 technologies) were defined from a national strategic plan. Second, the criticality of the criteria and alternatives were collected from subject matter experts. Third, the collected data acquired were analyzed using fuzzy TOPSIS, normalization, overlap analysis, agreement analysis, sensitivity analysis, ranking comparison, and Spearman correlation. Specifically, the criteria weightings are evaluated using fuzzy TOPSIS analysis that incorporates subjective and objective weights. Next, the Construction 4.0 technologies are ranked using fuzzy TOPSIS, and the critical ones are further refined using normalization value analysis. Then, the overlapping critical technologies between core values are appraised using overlap analysis. Additionally, sensitivity analysis is conducted to validate the ranking results. The robustness of the ranking performance is further evaluated using various metrics: Spearman's rank correlation coefficient, Kendall's Tau coefficient, root mean square error, and average absolute distance. This thorough ranking performance analysis establishes a comprehensive analysis of the ranking. Finally, the study analyzes the interrelationships between Construction 4.0 technologies and core values.

Overall, the study contributes to the Construction 4.0 body of knowledge by providing the following: (1) lists of critical Construction 4.0 technologies that enhance different organizational core values; (2) overview of overlapping and unique critical Construction 4.0 technologies in enhancing the core values; (3) validated rankings of the Construction 4.0 technologies between core values; and (4) insights into the relationships between Construction 4.0 technologies. The novelty of this study is the pioneering decision-making effort that laterally compares the impacts of Construction 4.0 technologies on multiple organizational core values. Additionally, the comparison provides a framework that allows top management to make informed decisions and navigate challenges associated with the adoption of Construction 4.0 technologies (Demirkesen and Tezel 2022; Olatunde et al. 2023). Any increase in the adoption of Construction 4.0 technologies can contribute to better project success, including reduced environmental impact and less pollution from construction projects (Nagy et al. 2021).

The rest of the paper is organized into various sections, as the "Literature Review" section consists of a literature review. Subsequently, the "Research methodology" section describes the research methodology in detail. Then, the "Results" section presents the overall results. The "Discussion" section focuses on critical discussion based on the study results, including study implications. Finally, the "Conclusion" section describes the conclusion of this study. Also, additional information is attached in the Appendix section.

Literature review

Overview of Construction 4.0 and organizational core values

Construction 4.0 employs a cyber-physical system to encourage the use of digitation in the built environment to achieve high performance (Osunsanmi et al. 2020). Construction 4.0 technologies provide organizations with the opportunity to enhance different organizational core values, including sustainability and resiliency, well-being, productivity, safety, and integrity (Kor et al. 2023). Tables 1 and 2 summarize prior works that explored Construction 4.0 technologies that target enhancement in the five organizational core values evaluated in this study. The following paragraphs discuss the prior works based on the five organizational core values.

Adopting Construction 4.0 technologies leads to enhanced sustainability and resiliency within the construction industry (Maqbool et al. 2022). Maqbool et al. (2022) and Sadeghi et al. (2022) explored the challenges of adopting Construction 4.0 technologies for enhancing sustainability. Maqbool et al. (2022) also evaluated the benefits of adopting Construction 4.0 technologies on sustainability. Then, Hao et al. (2021) and Musarat et al. (2023) investigated the impact of prefabrication on construction waste reduction. Sarker et al. (2020) used big data to link disaster information and systemic response for sustainability and resiliency enhancement. Finally, Sertyesilisik (2017) investigated the impact of BIM in enhancing disaster resiliency. Therefore, adopting Construction 4.0 technologies is proven by prior works to enhance sustainability and resiliency in construction.

The well-being of construction workers is compromised by demanding tasks, tight deadlines, long work hours, financial difficulties, and feelings of isolation (Rani et al. 2022). Nevertheless, a few works have emphasized the impacts of Construction 4.0 technologies in enhancing workers' well-being. For instance, Turner et al. (2021) proposed the adoption of site sensor data and wearable devices to accomplish the vision of good well-being among workers on-site. Moreover, Fagbenro et al. (2023) found that prefabricated construction enhances well-being by increasing physical monitoring and psychological work environments, lowering physical discomfort and fatigue, and fostering a good work-life balance. While Construction 4.0 technologies offer the potential for enhancing well-being in construction, prior works have often overlooked this core value (Duckworth et al. 2022). Thus, further investigation is needed to bridge the gap between well-being and Construction 4.0 technologies in the literature.

The construction industry exhibits lower productivity compared to other industries, and Construction 4.0 technologies have the potential to overcome this hurdle (Malomane et al. 2022; Maqbool et al. 2022; Sadeghi et al. 2022). Turner et al. (2021) highlighted the importance of data analytics and artificial intelligence (AI), robotics and automation, BIM, sensors and wearable devices, digital twins, and industrial connectivity to boost productivity. Meanwhile, (João Ribeirinho et al. 2020) proposed a model for assessing organizational readiness in adopting Construction 4.0 technologies to enhance productivity. Calvetti et al. (2020) investigated the potential use of sensors to predict the productivity of construction workers. Then, Feldmann (2022) explored barriers to automating prefabrication to solve productivity issues during construction. As evidenced by previous works, adopting Construction 4.0 technologies is crucial to enhance productivity in construction.

Apart from that, adopting Construction 4.0 technologies within the construction industry presents a compelling impact to enhance safety (Malomane et al. 2022). Therefore, Rodrigues et al. (2021) developed a plugin for BIM that detects hazards in the design phase to enhance construction safety. Meanwhile, Malomane et al. (2022) examined the challenges of adopting Construction 4.0 technologies to enhance safety management. Furthermore, Yang et al. (2023) proposed a deep-learning model to identify unsafe work behaviors among construction workers. Yap et al (2023) determined the most effective categories of Construction 4.0 technologies in enhancing safety management.

Table 1 List of Construction 4.0 technologies explored in other works

Construction 4.0 technologies	This study	Turner et al. (2021)	Fagbenro et al. (2023)	Calvetti et al. (2020)	(João Ribeirinho et al., 2020).	Feldmann (2022)	Rodrigues et al. (2021)	Malomane et al. (2022)	Yang et al. (2023)	Yap et al. (2023)	Sarker et al. (2020)	Dobrucali et al. (2022)	Sadeghi et al. (2022)	Hao et al. (2021)	Maqbool et al. (2022)	Musarat et al. (2023)	Sertyesilisik (2017)	Tao et al. (2022)	Chang et al. (2021)	Okedara et al. (2020)	Total
BIM	√	√					√	√		√		√				√	√	√			9
IoT	√	√		√	√			√		√		√			√				√		9
Big data and predictive analytics	√	√			√					√	√				√	√					7
Autonomous construction	√	√			√			√				√				√				√	7
Cloud and real-time collaboration	√				√										√						3
Advanced building materials	√																				1
AR and virtualization	√				√			√		√		√				√				√	7
Prefabrication and modular construction	√		√			√								√		√					5
AI	√	√			√			√	√			√				√				√	8
3D scanning and photogrammetry	√									√		√									3
3D printing and AM	√				√											√					3
Blockchain	√												√			√		√			4
Total	12	5	1	1	7	1	1	5	1	5	1	6	1	1	3	8	1	2	1	3	

BIM, building information modeling; *IoT*, Internet of Things; *AR*, augmented reality; *AI*, artificial intelligence; *AM*, additive manufacturing

Table 2 List of organizational core values targeted in other Construction 4.0 technology works

Organizational core values	This study	Turner et al. (2021)	Fagbenro et al. (2023)	Calvetti et al. (2020)	(João Ribeirinho et al. 2020)	Feldmann (2022)	Rodrigues et al. (2021)	Malomane et al. (2022)	Yang et al. (2023)	Yap et al. (2023)	Sarker et al. (2020)	Dobrucali et al. (2022)	Sadeghi et al. (2022)	Hao et al. (2021)	Maqbool et al. (2022)	Musarat et al. (2023)	Sertyesilisik (2017)	Tao et al. (2022)	Chang et al. (2021)	Okedara et al. (2020)	Total
Sustainability and resiliency	√										√		√	√	√	√	√				7
Well-being	√	√	√																		3
Productivity	√	√		√	√	√							√		√						7
Safety	√						√	√	√	√		√									6
Integrity	√																	√	√	√	4
Total	5	2	1	1	1	1	1	1	1	1	1	1	2	1	2	1	1	1	1	1	

Besides, Dobrucali et al. (2022) evaluated the impact of Construction 4.0 technologies to enhance construction safety. Hence, prior works demonstrated that adopting Construction 4.0 technologies is crucial to enhancing construction safety.

Integrity is essential in the construction industry for better transparency, honesty, and fairness (Roy et al. 2021). As such, Tao et al. (2022) introduced a blockchain framework for ensuring data integrity during design collaboration. Then, Chang et al. (2021) determined mitigating actions for addressing integrity issues of IoT in smart homes. Nevertheless, Okedara et al. (2020) disclosed that there is limited work in the current body of knowledge on integrity and Construction 4.0 technologies. As such, that work suggests further and deeper exploration of this topic to enhance integrity in construction.

Multi-criteria decision-making tools

Prior works on Construction 4.0 technologies and decision-making have emerged in recent years, including using MCDM methods (Shafei et al. 2022). MCDM is a powerful approach that aids complex decision-making processes by providing the best option of alternatives based on the weighting importance of the selection criteria. Table 3 presents the advantages and disadvantages of the most commonly used MCDM methods. These are analytic hierarchy process (AHP), TOPSIS, višekriterijumsko kompromisno rangiranje (VIKOR), preference ranking organization method for enrichment (PROMETHEE), and analytic network process (ANP) (Basílio et al. 2022). In addition to the basic MCDM methods, prior works have extensively employed fuzzy MCDM methods to aid decision-making processes, such as fuzzy AHP, fuzzy TOPSIS, fuzzy VIKOR, fuzzy PROMETHEE, and fuzzy ANP (Wang et al. 2023). These fuzzy MDCM methods use fuzzy set theory and logic controller as linguistic terms (Aslan et al. 2017, 2022). In addition, hybrid MCDM and advanced versions of fuzzy MCDM have been proposed to optimize decision processes (Al Mohamed et al. 2023; Al Mohamed and Al Mohamed 2023; Al Mohamed and Jeblak 2021; Bouraima et al. 2023; Deveci et al. 2023a, b; Deveci et al. 2023a, b; Qahtan et al. 2023; Saha et al. 2023). Nevertheless, fuzzy set theory excels in handling uncertain and vague data, offering effective information extraction from linguistic data (Singh et al. 2022a, b).

While each MCDM method has advantages and disadvantages, this study has opted for fuzzy TOPSIS as the primary method due to its alignment with the decision-making problem. Despite the limitations associated with TOPSIS, it is the most suitable among other methods for this study. Given the multi-criteria (five core values) and alternatives (twelve Construction 4.0 technologies) in this study, TOPSIS emerges as the most appropriate solution. It offers a

Table 3 Advantages and disadvantages of the MCDM method

MCDM method	Advantages	Disadvantages
AHP	• Use a hierarchy system and pairwise comparison • Help identify inconsistencies in decision models	• Fail to accommodate a large number of criteria and alternatives due to the pairwise comparison concept • Ineffective for complex decision-making
TOPSIS	• Suitable for handling a large number of criteria and alternatives • Provide a direct rating and simplicity in decision evaluation	• Absence of built-in inconsistency check in the decision model • Crisp data ignores the uncertainty and imprecision of decision
VIKOR	• Provide a preliminary understanding of the compromise solution at the beginning of the system design • It does not require a consistency check	• Inconsistent results due to rank reversal phenomenon • Complex computational procedures
PROMETHEE	• Provide transparent decision-making processes with specific characteristics and clearness • Use an outranking approach and pairwise comparison	• Complicated comparison between factors, time-consuming, and there is a lack of decision vision for a large number of criteria • Rank reversal problem
ANP	• Consider feedback relations and interdependencies among criteria and alternatives • Inclusion of interdependence of alternatives in network structure	• Complex computational procedures • Rank reversal problem

Sources: Abdullah et al. (2023); Chou (2018); Feng et al. (2020); Lazar and Chithra (2021); Oubahman and Duleba (2021); Papathanasiou (2021); Ren et al. (2022); Sen et al. (2015); Uzun et al. (2021); Zimonjić et al. (2018)

straightforward concept based on a numerical framework (Uzun et al. 2021). Although the method does not allow for evaluating inconsistency among expert judgments, using direct ratings in TOPSIS presents a practical solution for managing a larger number of criteria and alternatives. To address the crispness limitation of TOPSIS, it is essential to integrate fuzzy-based theory (Abdullah et al. 2023). Integration of fuzzy TOPSIS enables capturing ambiguity and uncertainty when selecting Construction 4.0 technologies. In the case of potential rank reversal in TOPSIS, this study employs entropy calculation (objective weight) to solve the problem (Wang and Lee 2009). Additionally, it is crucial to conduct a sensitivity analysis, as Singh et al. (2022a, b) recommended, to identify any inconsistencies in the rankings of alternatives. Thus, due to these considerations, the fuzzy TOPSIS method that incorporates subjective and objective weights has been chosen for determining criteria weights and ranking the alternatives in this study.

Knowledge gap

The literature review above indicates that existing works primarily focus on the impacts of one or several Construction 4.0 technologies on one or, at most, two organizational core values. Most existing works focused on assessing the impact of one technology on one core value (Calvetti et al. 2020; Chang et al. 2021; Fagbenro et al. 2023; Feldmann 2022; Hao et al. 2021; Sarker et al. 2020; Sertyesilisik 2017; Yang et al. 2023). Additionally, some works explored the impact of a few technologies on one core value (Dobrucali et al. 2022; Malomane et al. 2022; Musarat et al. 2023; Okedara et al. 2020; (João Ribeirinho et al. 2020); Tao et al. 2022; Yap et al. 2023). Then, there was an existing work that investigated the impact of one technology on two core values (Sadeghi et al. 2022), while others delved into a few technologies affecting two core values (Maqbool et al. 2022; Turner et al. 2021). Consequently, these existing works reveal a significant knowledge gap in the current literature, specifically regarding the absence of comprehensive assessments addressing various technologies that may impact different core values. Hence, a crucial need exists in the body of knowledge to compare the impact of various technologies on different core values to guide decision-makers in making technology investments (Khan et al. 2023; Shafei et al. 2022). Moreover, while most existing works focus on sustainability and resiliency, productivity, and safety, less attention is directed toward the impact of Construction 4.0 technologies on well-being and integrity (Okedara et al. 2020; Duckworth et al. 2022). Therefore, this study aims to fill this knowledge gap by comparing the impact of Construction 4.0 technologies on different organizational core values. The study findings offer practical propositions to guide construction organizations in achieving a holistic enhancement of sustainability and resiliency, well-being, productivity, safety, and integrity. To the best of our knowledge, the originality of this paper lies in its comprehensive assessment of critical Construction 4.0 technologies that enhance all five core values, thus contributing significantly to the existing body of knowledge.

Theoretical framework of this study

The previous subsection underscores the prevailing knowledge gap in existing works, emphasizing the need for a comprehensive comparison of the impacts of Construction 4.0 technologies on different organizational core values. Existing works indicated a lack of comprehensive assessments of the impacts of various Construction 4.0 technologies on different organizational core values and limited attention to certain core values. This signifies a significant knowledge gap in the current body of knowledge that demands comprehensive evaluation. Therefore, this study aims to address this knowledge gap by proposing a holistic theoretical framework that goes beyond the isolated works of individual core values, as illustrated in Fig. 1.

Compared to existing works, this theoretical framework offers a more encompassing view of the impacts of Construction 4.0 technologies on different organizational core values. By simultaneously considering different core values and exploring interrelationships between Construction 4.0 technologies and these values, the framework provides a holistic perspective that is essential for informed decision-making. This theoretical approach aligns with the increasing interest among decision-makers in adopting advanced technologies to optimize organizational performance (CalışDuman and Akdemir 2021; Queiroz et al.

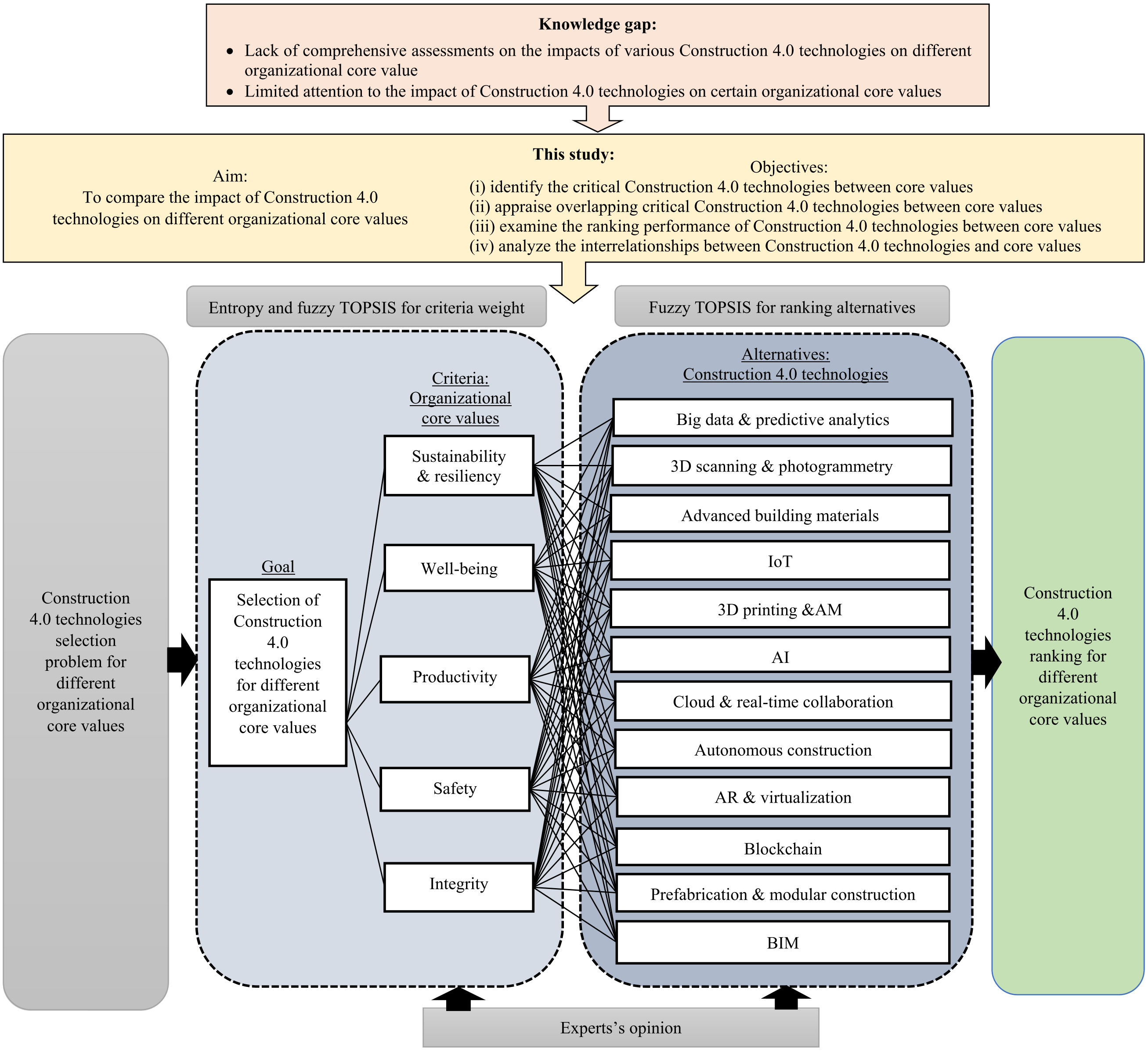

Fig. 1 Theoretical framework for selecting Construction 4.0 technologies for different organizational core values

2022). The framework highlights the criticality of overlapping Construction 4.0 technologies on different core values, emphasizing their utmost importance for adoption. Moreover, the selected methodology, fuzzy TOPSIS, serves as the practical foundation for this theoretical framework due to its ability to handle diverse criteria and alternatives. Then, the framework's robustness is further enhanced through sensitivity analysis and various ranking performance metrics, ensuring the reliability of ranking results. Therefore, the theoretical framework of this study is deemed comprehensive for advancing understanding of the complex interplay between Construction 4.0 technologies and organizational core values.

In summary, this study bridges a significant knowledge gap in the literature by conducting a comprehensive assessment of Construction 4.0 technologies, considering their impacts on all five organizational core values, and exploring potential interrelationships. The chosen methodology, fuzzy TOPSIS, adds practicality to the analysis, contributing substantially to the existing body of knowledge in the field of Construction 4.0.

Research methodology

Figure 2 shows the overall methodological framework for this study. The TOPSIS method was selected to achieve the study aim as justified in the "Literature review" section (see "Multi-criteria decision-making tools" section). However, traditional TOPSIS has limitations in handling decision-making imprecision and ambiguity, making fuzzy TOPSIS the preferred approach (Chowdhury and Paul 2020). By integrating fuzzy set theory, fuzzy TOPSIS effectively manages uncertain and vague data using linguistic terms (Chen 2000). Then, experts utilize these linguistic terms to assess criteria importance and prioritize alternatives, subsequently converting them into triangular fuzzy numbers (see Table 8 in Appendix).

Phase 1: instrument development

In fuzzy TOPSIS, it is necessary to develop a data collection instrument to gather expert opinions (Singh et al. 2022a, b). To develop the instrument, a decision matrix for the criteria and alternatives was formulated based on a national strategic plan for Construction 4.0 (CIDB 2020). Here, five criteria and twelve alternatives were adopted. Table 4 shows the criteria and alternatives used in the data collection instruments with their definitions. The developed instrument consists of three sections. The first section comprised the respondent's background. Then, the second section lays out an example page that guides experts in rating the criteria and alternatives. Finally, the last section allowed the experts to assign linguistic ratings to the adopted criteria and alternatives. A pilot study was carried out to check the appropriateness and clarity of the developed instrument. Five doctoral researchers and two professors in construction project management participated in this pilot study. Once the instrument was deemed suitable, it was finalized and ready for data collection.

Phase 2: data collection

Once the fuzzy TOPSIS data collection instrument was developed, this study proceeds with determining the target sample for the data collection. The target sample in fuzzy TOPSIS requires experts with specific characteristics, including work experience, diverse backgrounds, and relevance to the studied subject (Cooke and Goossens 1999). To fortify the reliability of the study, a discerning selection process is imperative, wherein experts must demonstrate professional knowledge in the field and a minimum of 5 years of practical experience or academic expertise (Al Mohamed and Al Mohamed 2023). Adopting judgmental sampling facilitated deliberate expert selection based on relevant experience and diverse backgrounds, optimizing their ability to assess criteria and alternatives effectively (Lazar and Chithra 2021). Consequently, fourteen experts from varied backgrounds, including clients, consultants, contractors, and academics, with work experience ranging from 5 to 38 years, were chosen to provide opinions using judgmental sampling (refer to Table 7 in Appendix for detailed information). While fuzzy TOPSIS typically requires a minimum of four experts (Cooke and Goossens 1999), the selection of fourteen experts aligns with common practices in construction project management research, where three to five experts are standard (Mahpour, 2018), ensuring the adequacy of collected data for subsequent analysis.

To address potential challenges during data collection, a pre-collection briefing was conducted, familiarizing experts with the instrument. Additionally, a sample rating section was provided in the instrument to guide experts in providing accurate opinions and avoiding risks of input errors. Also, the authors actively participated in the entire data collection process, offering clarifications to address any potential misunderstandings. Therefore, this meticulous approach resulted in collecting fourteen valid responses, forming robust inputs for further detailed data analysis.

Phase 3: data analysis

Reliability analysis

Cronbach alpha Before applying fuzzy TOPSIS for identifying critical Construction 4.0 technologies, it is essential to

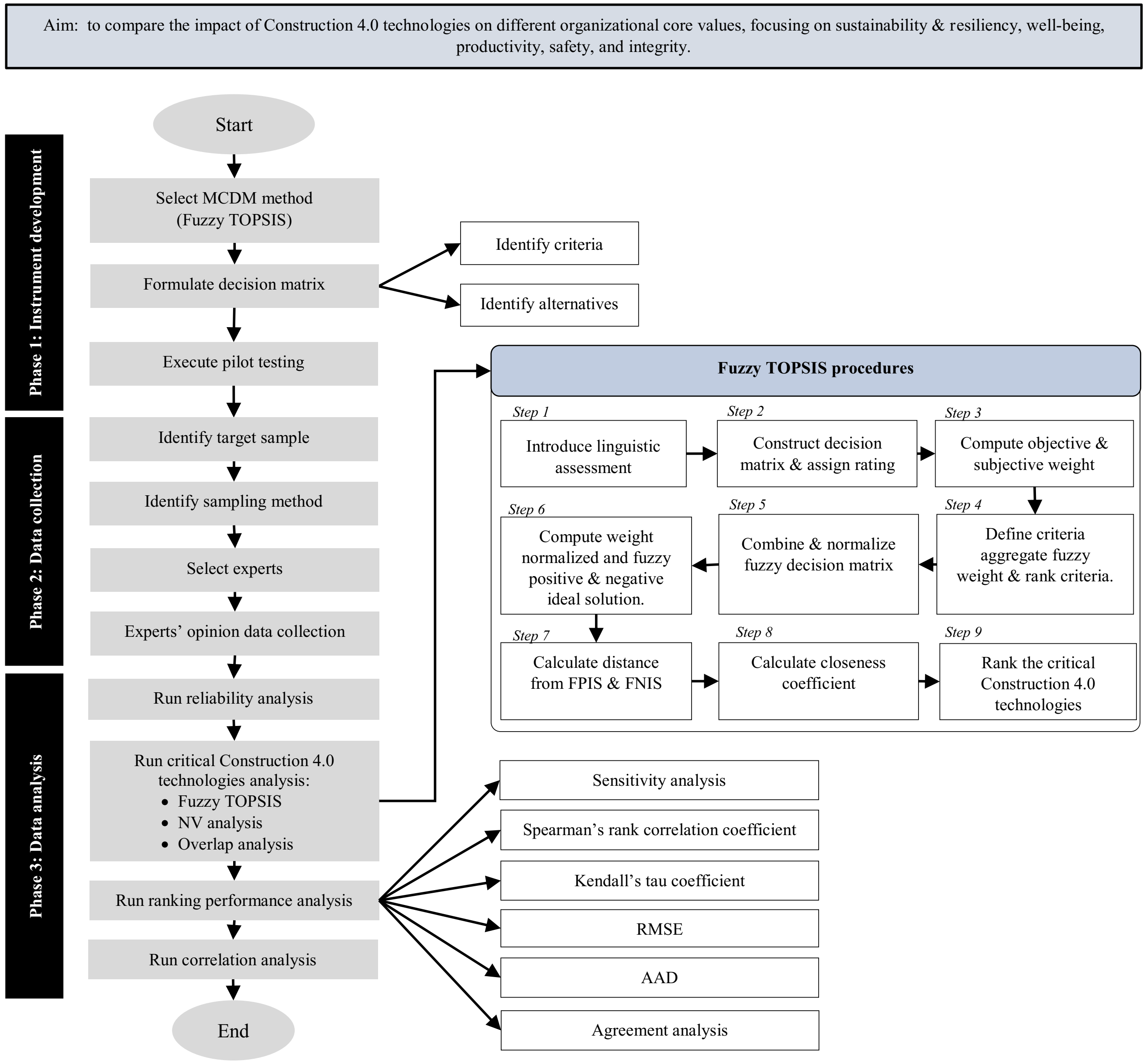

Fig. 2 A methodological framework for Construction 4.0 technology selection

ensure that the collected data is reliable using Cronbach's alpha. This analysis produces a coefficient that ranges from 0 to 1, with values above 0.70, signifying a high level of internal consistency within the collected data (Kumar et al. 2021).

Kendall's W Then, this study used Kendall's W test to measure the agreement of different experts on their rankings of organizational core values and Construction 4.0 technologies. The interpretation of Kendall's W is as follows: "0 to 0.09" is no agreement; "0.10 to 0.29" is weak agreement; "0.30 to 0.59" is moderate agreement; "0.60 to 0.99" is strong agreement; and "1" is a perfect agreement (Lazar and Chithra 2021).

Critical Construction 4.0 technology analysis

Fuzzy TOPSIS This study adopted fuzzy TOPSIS to identify the critical Construction 4.0 technologies in enhancing the five organizational core values (i.e., sustainability and resiliency, well-being, productivity, safety, and integrity). To ensure a robust methodology, the study integrates fuzzy TOPSIS analysis with the extension of subjective and objective weights, as proposed by Wang and Lee (2009),

Table 4 The criteria and alternatives used in the data collection instrument (sources: (CIDB 2020, 2021))

Indicators		Definition
Criteria	Sustainability and resiliency	Sustainability refers to a reduction of environmental effects, and resiliency is the ability to withstand disasters
	Well-being	Work-life balance for a positive and healthy workplace environment
	Productivity	Quality of work and efficiency in meeting project deadlines
	Safety	Effective safety programs for the prevention of accidents in construction sites
	Integrity	Ethical behavior of stakeholders in the organization
Alternatives	BIM	The digital representation that integrates the architectural, engineering, and construction (AEC) in a centralized system for optimizing the lifecycle of building performance
	AR and virtualization	Technologies that allow human and computer interaction and differentiate virtual and real objects
	Blockchain	Distributed ledger technology that allows for the secure storage of information, records of transactions, internet protocol, and other types of data in computer network
	IoT	Network of interconnected devices and objects that collect, exchange, and analyze data through the internet
	Cloud and real-time collaboration	Internet-centric to assist construction professionals with unrestricted access to manufacturing information and a vast quantity of storage resources
	Big data and predictive analytics	Technologies that efficiently manage large quantities of project data by storing, managing, and processing through commodity server
	Autonomous construction	Automatic assembly and execution of construction tasks using robots controlled through computer processes and mechanization
	3D printing and AM	A process for creating or recreating a physical object using a digital model by depositing layers of materials
	Prefabrication and modular construction	Production of volumetric units or components of building construction systems in a factory setting
	Advanced building material	Development of new or enhanced industrial materials using the integration of new technologies and processes
	AI	The capability of machines to imitate and replicate human cognitive functions via algorithm
	3D scanning and photogrammetry	Data acquisition and mapping techniques enable the creation of 3D models from photographs to monitor changes

as presented in Table 5. Subjective methods derive weights exclusively from expert judgments, with subsequent mathematical applications determining the overall evaluation of criteria. Conversely, objective weights are determined by automatically solving mathematical models without expert input (Kacprzak 2021).

The entropy method, introduced by Shannon and Weaver (1949), stands out as a popular approach for determining objective weights. However, the choice between subjective and objective weights hinges on specific decision problem characteristics, criteria nature, and available resources for data collection and analysis (Zoraghi et al. 2013). While objective weighting is particularly applicable in scenarios where reliable subjective weights are unattainable (Deng et al. 2000), it tends to overlook the significant judgments contributed by experts. Grounded in mathematical models, objective approaches may neglect the wealth of subjective insights offered by experienced professionals. Objective weights become a pragmatic recourse in situations where obtaining subjective weights is challenging or expensive or when experts are unable to express preference information between criteria (Kacprzak 2021; Wen et al. 2019). In contrast, while reflecting the expert's judgment, subjective approaches may introduce bias into alternative rankings if the experts have limited knowledge or experience (Zoraghi et al. 2013).

Given the absence of limitations in obtaining expert opinions and the experts' wealth of experience and professional expertise in the subject area, this study applies Shannon's entropy (objective weight) as a basis to support subjective weights (Wang and Lee 2009). Moreover, in construction project management research, it is advisable to gauge criteria weights through the discerning judgment of respective experts, thereby enhancing the credibility of the potential ranking outcome (Shamsuzzoha et al. 2021). As such, the preference for subjective weight in this construction project management domain is justified. Therefore, incorporating the information entropy concept (objective weight) in this study serves the purpose of additional validation of the subjective weight, effectively ensuring a harmonious balance between them.

Normalization value analysis Normalization value (NV) analysis evaluates the critical factors by normalizing the data

Table 5 The fuzzy TOPSIS steps

Step no	Description	Equation (Eq)	Eq no
Step 1	*Introduce the linguistic assessment scale and triangular fuzzy numbers* The linguistic terms and triangular fuzzy numbers for criteria and alternatives are shown in Appendix (Table 8)	-	-
Step 2	*Construct a decision matrix and assign linguistic evaluations to alternatives against criteria* Selection criteria are referred to n where $C_{j,}(j = 1, 2, \ldots n)$ and alternative m, where $(A_{i,} i = 1, 2, \ldots m)$ are ranked by the experts. In this step, subjective assessment is executed by the experts to measure the weighting vector $W = \left(w_1, w_2, \cdots, w_n, \cdots, w_j\right)$. The decision matrix $X = (X_{ij,} i = 1, 2, \ldots m; j = 1, 2, \ldots n)$ denotes the rating of alternatives A_i against selection criteria C_j as shown in Appendix (Table 9). The decision matrix formulation is as Eq. (1)	$D = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} C_1 C_2 \cdots C_n \\ \left\{\begin{array}{ccc} X_{11} & X_{12} & X_{1n} \\ X_{21} & X_{22} & X_{2n} \\ X_{m1} & X_{m2} & X_{mn} \end{array}\right\} \end{array}$	Eq. (1)
Step 3	*Compute criteria aggregated fuzzy weights (subjective weight) and objective weight* (a) Subjective assessments are made to determine experts' weights for criteria as shown in Appendix (Table 10). The equation for subjective assessment is as Eq. (2)	$\widetilde{W}_j = \frac{1}{n}\left(\sum_{i=0}^{n} W_j^e\right)$ $j = 1, 2, ..., n$	Eq. (2)
	(a) Objective weight is measured using entropy measure as shown in Appendix (Table 11). The decision matrix must be normalized for each criterion via the entropy method to obtain the projection value using Eq. (3)	$P_{ij} = \frac{x_{ij}}{\sum_{j=1}^{m} X_{ij}}$	Eq. (3)
	After the decision matrix has been normalized, entropy values e_j is calculated using Eq. (4)	$e_j = -k \sum_{j=1}^{n} p_{ij} lnp_{ij}$ $k\mathrm{isconstantwhere}k = \frac{1}{\ln(m)}$	Eq. (4)
	Then, the degree of divergence d_j for each criterion is calculated using Eq. (5)	$d_j = 1 - e_j$	Eq. (5)
	The higher the divergent value, the greater the importance of the criteria. Then, the objective weight is determined using Eq. (6)	$W_j = \frac{d_j}{\sum_{k=1}^{n} d_k}$	Eq. (6)
Step 4	*Calculate the aggregate fuzzy weight for each criterion* W_{ij} The aggregate fuzzy weight for each $criterion W_{ij}$ is calculated as shown in Appendix (Table 10) using Eq. (7)	$\widetilde{X}_{ij} = \frac{1}{n}\left(\sum_{e=1}^{n} \widetilde{x}_{\mathrm{j}}^{\mathrm{e}}\right)$ $i = 1, 2, ..., n$	Eq. (7)
Step 5	*Normalize the fuzzy decision matrix for alternatives* The normalized value for the decision matrix is determined based on benefit-related criteria and cost-related criteria, as shown in Appendix (Table 12) using Eq. (8)	$\widetilde{r}_{ij} = \left\{\left(\frac{a_{ij}}{c_{ij}^+}, \frac{b_{ij}}{c_{ij}^+}, \frac{b_{ij}}{c_{ij}^+}\right), j \in B\right.$ $\widetilde{r}_{ij} = \left\{\left(\frac{a_{ij}}{c_{ij}^+}, \frac{b_{ij}}{c_{ij}^+}, \frac{b_{ij}}{c_{ij}^+}\right), j \in C\right.$ $c_j^+ = Max_i c_{ij} if j \in B$ $a_j^- = Min_i a_{ij} if j \in C$	Eq. (8)
Step 6	*Compute weight normalized matrix and fuzzy positive and negative ideal solution* The weight-normalized matrix is calculated in Appendix (Table 12) using Eq. (9)	$\widetilde{V} = \left[\widetilde{v}_{ij}\right]_{mxk,} i = 1, 2, \ldots, m;$ $j = 1, 2, ..., n$ $\widetilde{v}_{ij} = \widetilde{r}_{ij} \varnothing \widetilde{W}^{ij}$	Eq. (9)
Step 7	*Calculate the distance from FPIS and FNIS for each of the alternatives* Next, the fuzzy positive ideal solution (FPIS) and fuzzy negative solution (FNIS) are computed using Eq. (10)	$\mathrm{FPIS} = \left(\widetilde{v}_1^+, \widetilde{v}_2^+, \cdots \widetilde{v}_k^+\right)$ $\mathrm{FNIS} = \left(\widetilde{v}_1^-, \widetilde{v}_2^-, \cdots \widetilde{v}_k^-\right)$	Eq. (10)
	The distance of each alternative from FPIS and FNIS is presented in Appendix (Table 13) using Eq. (11)	$d\left(A_1, A_2\right) = \sqrt{\frac{\sum_3^{h=1}\left(x_h - y_h\right)}{3}} A_1 = a_1 b_1 c_1$ $A_2 = a_2 b_2 c_2$	Eq. (11)
Step 8	*Calculate the closeness coefficient* (CC_i) *and rank the best alternatives from high to low* CC_i *value* Calculated CC_i values are presented in Table 6 using Eq. (12)	$CC_i = \frac{d_i^-}{d_{ij}^+ + d_{ij}^-}$ $i = 1, 2, \cdots, m$	Eq. (12)
Step 9	*Selection of critical Construction 4.0 technologies* The most critical Construction 4.0 technologies are farthest from FNIS and closest to FPIS. Thus, to prioritize critical Construction 4.0 technologies, the ranking for CC_i are in descending order, as shown in Table 6	-	-

to a scale between 0 and 1. A value greater than 0.5 indicates a high criticality level (Lee et al. 2021). This study used CC_i values obtained from fuzzy TOPSIS for NV.

Overlap analysis The overlap analysis is a decision-making technique that compares the similarities and differences between multiple groups (Al-Mohammad et al. 2022). After identifying the critical Construction 4.0 technologies, this study utilized the overlap analysis to identify the overlapping critical technologies between the five core values. Previous works have also used this technique. For example, Al-Mohammad et al. (2022) identified the overlapping critical factors affecting BIM adoption between countries with distinct income levels. King et al. (2022) investigated the overlapping critical pandemic impact between different organizational characteristics. In this study, technologies that overlap in multiple core values are considered critical, and those only present in one group are deemed less critical.

Ranking performance analysis

Sensitivity analysis This study ran a sensitivity analysis to test the robustness of the ranking of Construction 4.0 technologies. This technique assesses the influence of criteria weight affecting the ranking of the alternatives to tackle uncertainties in expert judgment (Singh et al. 2022a, b). Therefore, in this study, ten different scenarios were conducted with criteria weights ranging from "least important" (1,1,3) to "most important" (7,9,9), as shown in Appendix (Table 15).

Spearman's rank correlation coefficient Spearman's rank correlation coefficient (ρ) is used in this study to establish the descriptive comparison of rankings to determine any statistical significance (Mahamadu et al. 2020).

The equation for ρ is:

$$\rho = \frac{6\sum \sigma_i^2}{n^3 - n} \tag{13}$$

Kendall's Tau coefficient Kendall's Tau coefficient (τ) is used in this study to establish the correlation coefficient between the rank pairs of the Construction 4.0 technologies, with a lower τ indicating that the value is statistically significant (Lai and Xu 2019).

The equation for τ is:

$$\tau = \frac{\sum C_{ij} + \sum D_{ij}}{\sum C_{ij} - \sum D_{ij}} \tag{14}$$

Root mean square error (RMSE)

RMSE is utilized to assess the ranking quality of Construction 4.0 technologies. It compares predicted and actual rank to measure the overall ranking performance, with a smaller RMSE value indicating a better ranking performance (Singh et al. 2022a, b).

The equation for RMSE is:

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(R_{\mathrm{obs},i}\_R_{\mathrm{act},i})^2}{n}} \tag{15}$$

where $R_{\mathrm{obs},i}$ is the predicted rank and $R_{\mathrm{act},i}$ is the actual rank.

Average absolute distance (AAD) AAD is employed to measure the accuracy of ranking performance based on the relative distance between the predicted and the actual ranks, with a lower AAD value indicating good ranking performance (Singh et al. 2022a, b).

The equation for AAD is:

$$\mathrm{AAD} = \frac{\sum_{i=1}^{n} |R_i - A_i|}{n} \tag{16}$$

where R_i is the predicted rank, and A_i is the actual rank for the *i*th observation.

Agreement analysis Then, agreement analysis was carried out to identify areas of agreement or disagreement among the experts on the ranking of the Construction 4.0 technologies. The rank agreement factor (RAF) is used to determine the absolute difference in rankings between core values by a pairwise approach (Badraddin et al. 2022). The RAF technique uses a mathematical equation that considers N to represent the total number of items; the rank of the i^{th} item in group 1 is R_{i1} and in group 2 is R_{i2}; and $R_{j2} = N\text{-}R_{i2}+1$. In this study, N equals twelve (the number of alternatives). The agreement percentage is calculated by the following:

The equation for the mean value of total ranks is

$$\mathrm{RAF} = \frac{1}{N}\sum_{i=1}^{N}{}_{i}(R_{ij}) \tag{17}$$

The equation for RAF is

$$RAF = \frac{1}{N}\sum_{i=1}^{N} |R_{i1} - R_{i2}| \tag{18}$$

Equation (18)

The equation for maximum RAF is

$$\mathrm{RAF}_{\max} = \frac{1}{N}\sum_{i=1}^{N} \left|R_{i1} - R_{j2}\right| \tag{19}$$

The equation for percentage disagreement (PD) is

$$\mathrm{PD} = \frac{\sum_{i=1}^{N} |R_{i1} - R_{i2}|}{\sum_{i=1}^{N} \left|R_{i1} - R_{j2}\right|} x100 \tag{20}$$

The equation for percentage agreement (PA) is

$$\mathrm{PA} = 100 - PD \tag{21}$$

Correlation analysis

After ranking performance analysis, this study executed correlation analysis to analyze the relationship between Construction 4.0 technologies using Spearman's correlation test. Correlation value can be interpreted as follows: 0.00 to 0.19

as a very weak correlation; 0.20 to 0.39 as a weak correlation; 0.40 to 0.59 as a moderate correlation; 0.60 to 0.79 as a strong correlation; and 0.80 to 1.00 as very strong correlation (Musarat et al. 2022).

Results

Reliability analysis

Cronbach alpha

This study computed two Cronbach's alpha values. First, the Cronbach's alpha value is 0.797 for the five core values. Then, the alpha value of 0.971 is obtained for the twelve Construction 4.0 technologies. As both values are higher than 0.70, the results indicate that the collected data have excellent reliability and internal consistency.

Kendall's W

Moving to Kendall's W test, experts exhibited weak agreement, with a W value of 0.201 (20.1% agreement) and statistically significant ($p < 0.001$). However, as the number of alternatives (Construction 4.0 technologies) exceeds seven, a Chi-square test is conducted. The computed Chi-square value (166.142) exceeded the critical value (98.340), affirming consistent and valid expert agreement for subsequent analysis.

Critical Construction 4.0 technology analysis

Fuzzy TOPSIS

This study employed the fuzzy TOPSIS method to assess the impact of Construction 4.0 technologies on five organizational core values. Figure 3 and Table 11 in Appendix show that productivity is the most important criterion from the entropy-based weighting (objective weight) results. It is followed by integrity, well-being, safety, and sustainability and resiliency. Meanwhile, Table 6 presents the ranked Construction 4.0 technologies based on CC_i values for the twelve alternatives according to the five core values. The closely obtained CC_i values signify the equal criticality of these technologies in enhancing all five core values, as shown in Fig. 4.

Normalization value analysis

Given the prior fuzzy TOPSIS results, which underscored the equal criticality of all Construction 4.0 technologies in enhancing all five core values, NV analysis is conducted to identify critical technologies further. Table 6 presents NV for each of the twelve technologies across every organizational core value. The results identified six critical technologies for sustainability and resiliency, six for well-being, five for productivity, six for safety, and five for integrity. Additionally, when considering the aggregate score, five of the twelve Construction 4.0 technologies exhibited NV values exceeding 0.50. Meanwhile, BIM scores NV values of 1.00 for three out of five organizational core values, as shown in Fig. 5.

Overlap analysis

Following NV analysis, overlap analysis was conducted to identify the overlapping critical Construction 4.0 technologies between five core values. Figure 6 shows that four technologies (BIM, IoT, big data and predictive analytics, and autonomous construction) overlap between all five core values. Additionally, cloud and real-time collaboration exhibits overlap among well-being, productivity, and integrity, while AR and virtualization overlap between well-being and safety.

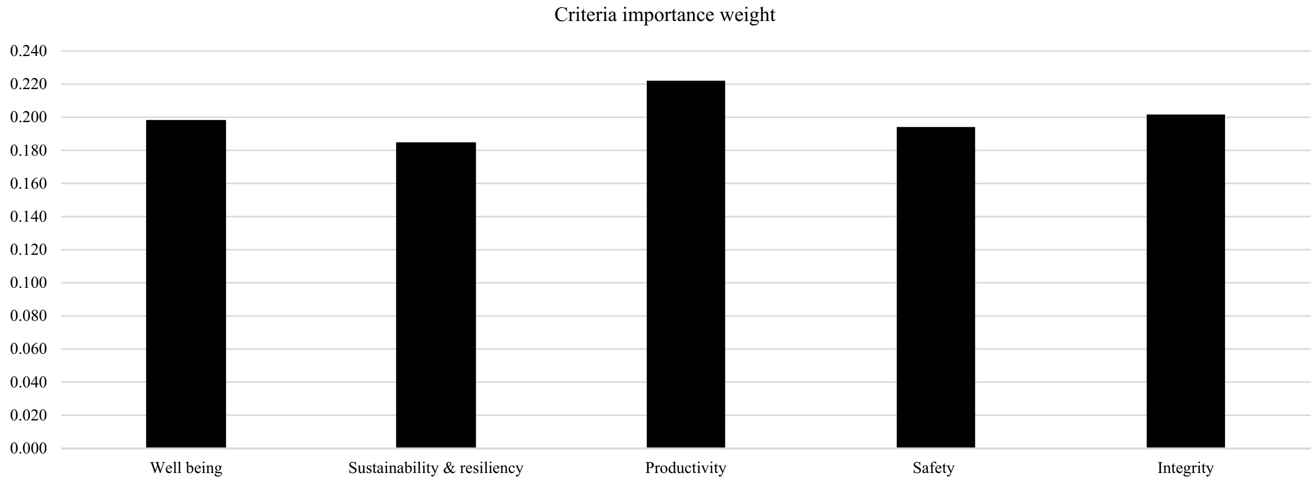

Fig. 3 Criteria importance weight

Table 6 CC_i, NV, and final ranking of Construction 4.0 technologies

Construction 4.0 technologies	Organizational core values																	
	Sustainability and resiliency			Well-being			Productivity			Safety			Integrity			Aggregate		
	CC_i	NV^a	R	CC_i	NV^a	R	CC_i	NV^a	R	CC_i	NV^a	R	CC_i	NV^a	R	CC_i	NV^a	R
BIM	0.562	1.000^b	1	0.554	0.840^b	4	0.643	1.000^b	1	0.512	0.622^b	4	0.549	1.000^b	1	0.562	1.000^b	1
IoT	0.538	0.583^b	5	0.557	0.881^b	3	0.592	0.551^b	3	0.528	1.000^b	1	0.533	0.682^b	2	0.549	0.747^b	2
Big data and predictive analytics	0.541	0.629^b	4	0.557	0.881^b	2	0.594	0.575^b	2	0.520	0.807^b	3	0.524	0.515^b	5	0.547	0.704^b	3
Autonomous construction	0.554	0.855^b	2	0.543	0.673^b	5	0.586	0.500^b	5	0.523	0.875^b	2	0.527	0.571^b	4	0.546	0.691^b	4
Cloud and real-time collaboration	0.527	0.394	8	0.565	1.000^b	1	0.589	0.526^b	4	0.504	0.435	9	0.533	0.682^b	2	0.543	0.634^b	5
Advanced building materials	0.551	0.806^b	3	0.522	0.371	9	0.580	0.448	7	0.507	0.498	7	0.513	0.288	9	0.534	0.465	6
AR and virtualization	0.516	0.199	11	0.543	0.673^b	5	0.583	0.474	6	0.509	0.560^b	6	0.513	0.288	9	0.532	0.432	7
Prefabrication and modular construction	0.535	0.536^b	6	0.525	0.412	7	0.560	0.276	8	0.507	0.498	7	0.519	0.402	6	0.529	0.378	8
AI	0.533	0.489	7	0.525	0.412	7	0.549	0.181	9	0.512	0.622^b	4	0.519	0.402	6	0.527	0.345	9
3D scanning and photogrammetry	0.527	0.394	8	0.511	0.207	11	0.549	0.181	9	0.502	0.373	10	0.519	0.402	6	0.521	0.233	10
3D printing and AM	0.527	0.394	8	0.497	0.000	12	0.537	0.080	11	0.502	0.373	10	0.499	0.000	12	0.512	0.062	11
Blockchain	0.505	0.000	12	0.514	0.249	10	0.528	0.000	12	0.486	0.000	12	0.513	0.288	9	0.509	0.000	12

CC_i closeness coefficient; NV^a normalized value; *R* rank; NV (CC_i−minimum CC_i) / (maximum CC_i − minimum CC_i); NV^b indicates critical technologies with $NV > 0.50$

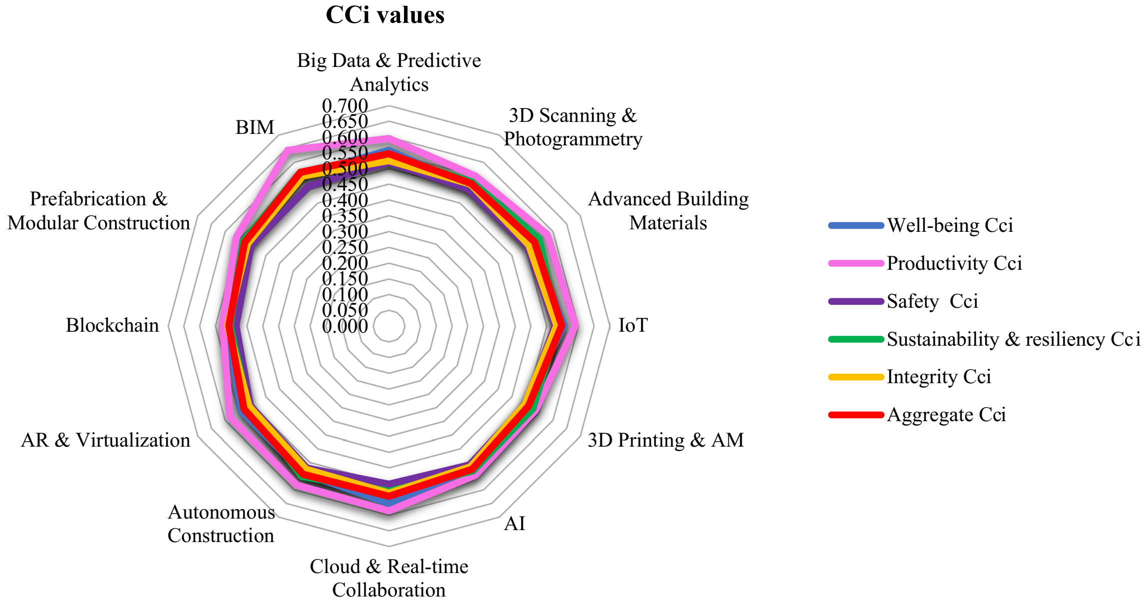

Fig. 4 CC_i values

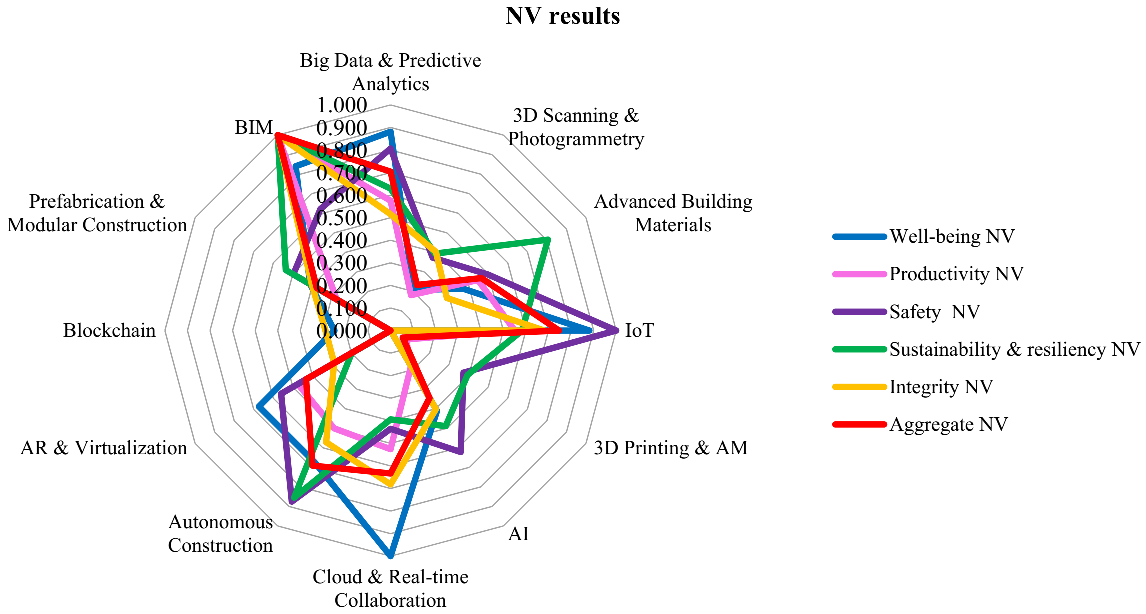

Fig. 5 NV results

Ranking performance analysis

Sensitivity analysis

This subsection assesses sensitivity analysis outcomes based on ten scenarios, detailed in Appendix (Table 15). The results unveil slight shifts in the first ranking under scenario 8, primarily attributed to changes in criteria weights, as depicted in Fig. 7. Furthermore, the fluctuation observed in rankings across the ten scenarios emphasizes the influence of criteria weight adjustments on alternative ranking.

Ranking performance comparison

The comparison of ranking performance based on sensitivity analysis scenarios is available in Appendix A (Table 16). Notably, ρ and τ values across all rankings closely approximate 1, indicating a strong correlation

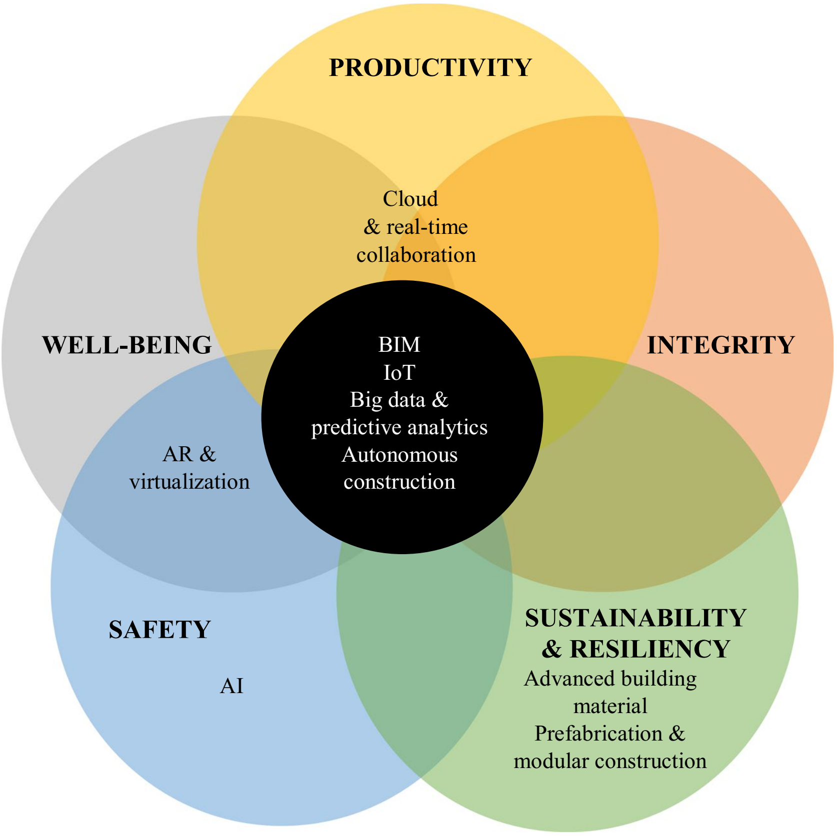

Fig. 6 Overlapping and non-overlapping of the Construction 4.0 technologies between organizational core values

between actual and predicted rankings. Furthermore, all RMSE values are consistently small for each scenario, affirming minimal distance between predicted and actual ranks. To support RMSE findings, AAD measurements reveal a narrow rank distance among Construction 4.0 technologies. In summary, employing these four established indicators, the ranking performance assessment validates the excellent ranking performance.

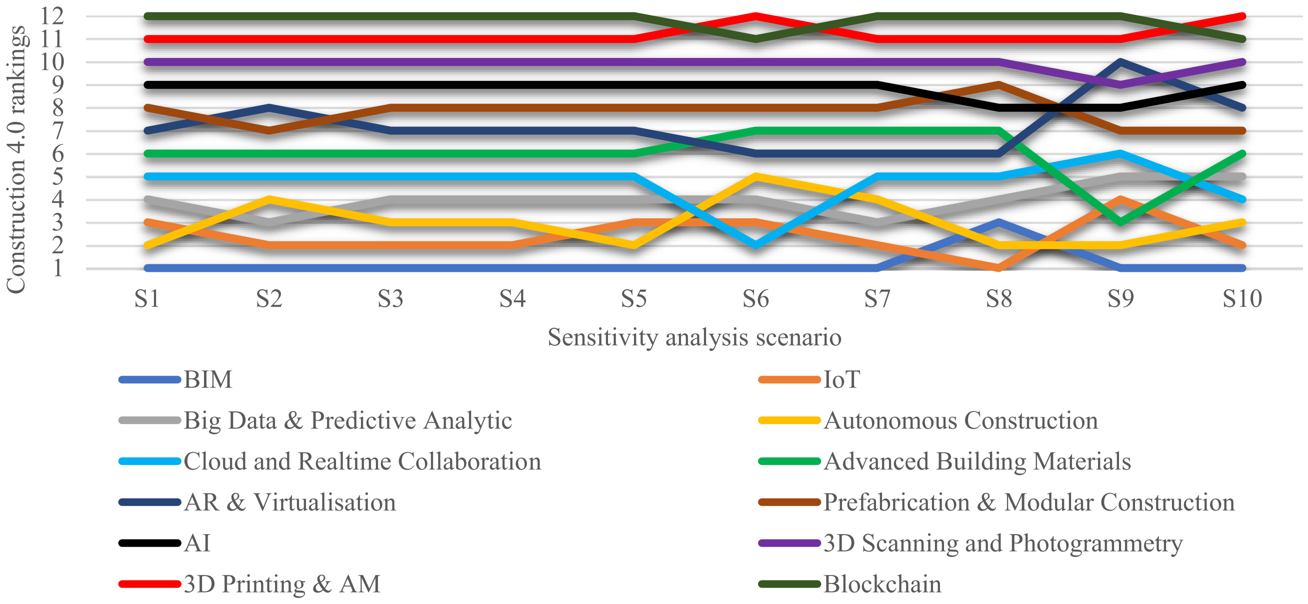

Fig. 7 Construction 4.0 technology rankings based on sensitivity analysis scenario

Agreement analysis

The percentage of agreement on the ranking of Construction 4.0 technologies between organizational core values is provided in Appendix (Table 14). A threshold of 55% for PAs signifies good ranking agreement (Zhang 2005). The PA results in this study span from 32 to 76%, with most exceeding the 55% benchmark, except for integrity and safety (47%), integrity and sustainability and resiliency (46%), and well-being and sustainability and resiliency (32%). The highest PA is observed between well-being and productivity, reaching 76%. These outcomes affirm good agreement in ranking Construction 4.0 technologies on different organizational core values, presented in Fig. 8.

Correlation analysis

The correlation analysis results between the different organizational core values for each Construction 4.0 technology are shown in Appendix (Table 17). Notably, AI exhibits the highest number of pairs (five) with "very strong correlations": well-being and productivity; well-being and safety; well-being and sustainability and resiliency; productivity and safety; and productivity and sustainability and resiliency. Additionally, advanced building materials have two "very strong correlation" pairs: well-being and productivity and productivity and sustainability and resiliency. Meanwhile, four Construction 4.0 technologies each exhibit one pair of "strong correlations": IoT (safety and integrity); cloud and real-time collaboration (well-being and productivity); blockchain (productivity and sustainability and resiliency), and prefabrication and modular construction (well-being and sustainability and resiliency). These findings reveal a moderate to strong relationship between the impacts of Construction 4.0 technologies on multiple organizational core values.

Discussion

This section discusses the results obtained in the "Results" section in light of the impacts of Construction 4.0 technologies on different organizational core values.

Critical Construction 4.0 technologies for all organizational core values

BIM

Referring to Table 6 and Fig. 6, this study unequivocally establishes BIM as the critical technology that enhances all five organizational core values studied. While various technologies make unique contributions, BIM's comprehensive integration of 3D modeling, data management, and collaboration tools yields critical impacts, enhancing sustainability and resiliency, well-being, productivity, safety, and integrity in construction (Toyin and Mewomo 2022). BIM is indispensable for reducing errors, rework, and waste, enhancing sustainability through digital models (Tam et al. 2021). This approach conserves materials, mitigates environmental impact, and enables virtual structural testing for defect detection and disaster resiliency (Sertyesilisik 2017). Moreover, BIM streamlines tasks like cost estimation, clash detection, site planning, digital fabrication, and 4D

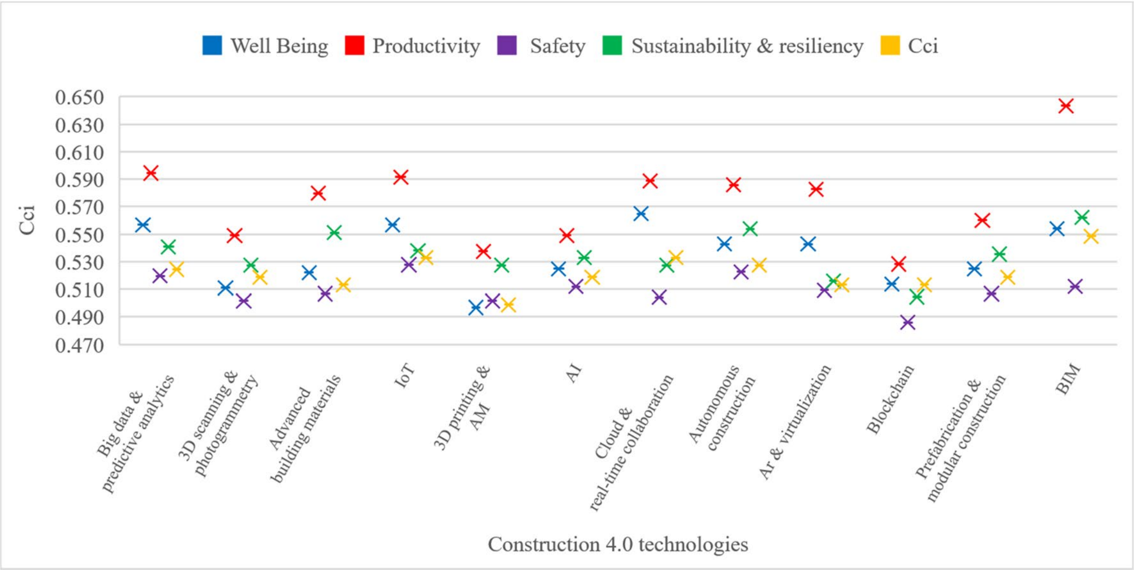

Fig. 8 Agreement analysis between organizational core values based on Construction 4.0 technology ranking

simulations, reducing workloads and stress while improving worker well-being (Tanko et al. 2022). Additionally, it significantly boosts construction productivity through 3D modeling, task automation, resource efficiency, and enhanced stakeholder communication (Yoo and Ham 2020). Regarding safety, BIM excels by early detection of design issues, integration with safety considerations, and enhancing hazard awareness during workers' training (Ganah and John 2017; Yap et al. 2023). Furthermore, BIM's documentation-sharing feature fosters transparency, accountability, and integrity by reducing the risk of data misuse (Hajj et al. 2021). Therefore, undeniably, given its critical impact on all five organizational core values, construction organizations must prioritize adopting BIM.

IoT

The construction industry has recently witnessed a surge in attention toward IoT. This study's findings disclose IoT's critical impact on all organizational core values despite its second-place ranking in aggregate (refer to Table 6). IoT is a powerful technology that utilizes sensors, internet connectivity, and analytics applications to detect and gather information (CIDB 2020). To enhance sustainability, IoT prevents noise pollution by identifying abnormal sounds in heavy construction equipment (Oke and Arowoiya 2021). Furthermore, this technology enhances disaster resiliency by swiftly identifying infrastructure failures through real-time data analysis, facilitating informed emergency responses, and minimizing construction disruptions (Damaševiˇ et al. 2023). Moreover, IoT devices such as electronic cardiograms, infrared sensors, and radar track various physiological metrics, including heart rate, body temperature, and blood oxygen, to ensure workers' well-being (Awolusi et al. 2018). Besides, IoT enhances productivity using sensor-enabled maintenance, thereby detecting abnormalities before equipment failures, minimizing delays, and reducing cost overruns (Oke and Arowoiya 2021). In contrast to the findings by Dobrucali et al. (2022), which emphasized BIM's role in safety enhancement, this study highlights IoT as the top contributor to safety (refer to Table 6). This is attributed to integrating IoT devices within personal protective equipment, enabling real-time safety monitoring, location tracking, and hazard warnings, ultimately enhancing safety in construction (Yap et al. 2023). Additionally, IoT enhances integrity in construction by offering data security, confidentiality, and the prevention of unauthorized data tampering (Oke et al. 2022). Undoubtedly, IoT presents high-impact capabilities that enhance sustainability and resiliency, well-being, productivity, safety, and integrity in construction.

Big data and predictive analytics

Another critical technology that imposes a high impact on all organizational core values is big data and predictive analytics. This is driven by their cost-effective storage and processing of vast real-time data (Singh et al. 2022a, b). Big data and predictive analytics empower sustainability by enabling data-driven decisions on energy consumption, resource efficiency, and waste management (Veras et al. 2018). Also, this technology enhances resiliency by offering early warnings, precise forecasts, and trends of disasters (Sarker et al. 2020). Over the years, construction workers frequently face stress, burnout, and other mental challenges (Tijani et al. 2021). Fortunately, big data and predictive analytics can detect these issues, aiding organizations in enhancing workers' well-being by identifying relevant trends and patterns. Moreover, this technology ensures precise cost forecasts aligned with client budgets, leveraging historical data and market trends, ultimately boosting profitability and preventing project delays, thereby enhancing construction productivity (Miranda et al. 2022). In addition, the Big Data Accident Prediction Platform (B-DAPP) enhances safety in construction by utilizing data-driven insights and accident records, worker profiles, project details, and environmental factors to prevent potential occupational accidents (Ajayi et al. 2019). Also, big data and predictive analytics excel in fraud and security breach detection, reducing the risk of unauthorized access and data breaches in organizations, thereby enhancing integrity in construction (Melo-Acosta et al. 2017). Considering these capabilities, the adoption of this technology is imperative in construction.

Autonomous construction

Finally, autonomous construction also poses a high impact to enhance all five organizational core values. It uses vehicles, robots, and drones to build structures without human supervision (Melenbrink et al., 2020). Autonomous construction, particularly through precise excavation technology, enhances environmental sustainability by minimizing material waste and preserving ecosystems (Jud et al. 2021). Furthermore, it allows organizations to maintain operations during disasters by automating tasks in hazardous areas and minimizing human presence on-site (Onososen and Musonda 2022). Additionally, it handles repetitive and labor-intensive on-site tasks like bricklaying, painting, loading, and bulldozing (Xu and de Soto 2020). This not only boosts job satisfaction but also reduces physical and mental strain, ultimately enhancing the well-being of construction workers. Besides, autonomous construction applied in activities such as concrete distribution, surface leveling, compaction, finishing, and painting reduces labor costs and enhances overall efficiency, resulting in increased construction productivity (Zhao et al., 2022). Moreover, autonomous construction's ability to handle repetitive tasks and operate in hazardous environments reduces 82% of construction accidents caused by human errors (Winge et al. 2019). Furthermore, adopting autonomy algorithms to check infrastructure defects streamlines collaboration between designers and professionals, enhancing integrity in construction. Therefore, as evidenced by several works, autonomous construction has high impacts that enhance sustainability and resiliency, well-being, productivity, safety, and integrity in construction.

Critical Construction 4.0 technology for well-being, productivity, and integrity

Cloud and real-time collaboration

The National Institute of Standards and Technology (NIST) defines cloud and real-time collaboration as a model that offers minimal management and the least service-provider interaction (Badger et al. 2012). The construction workers' mental health challenges are exacerbated by COVID-19's effects on job stability, working conditions, and health (Pamidimukkala and Kermanshachi 2021). These issues prompt smaller construction organizations to adopt cloud and real-time collaboration for business survival, as it offers remote discussion and work flexibility, thus fostering workers' well-being (Du Plessis and Simpson 2021). Moreover, this technology enhances productivity by empowering construction stakeholders to collaborate remotely, swiftly share information, resolve issues, and make decisions (Oke et al. 2021). Besides, recent advancements in cloud security, including encryption, cutting-edge software, cyber insurance, and audits, deter misconduct among construction stakeholders, thereby promoting integrity in construction (Bello et al. 2021). Therefore, considering these, cloud and real-time collaboration proved critical to enhance well-being, productivity, and integrity in construction.

Critical Construction 4.0 technologies for well-being and safety

AR and virtualization

Finally, AR and virtualization are Construction 4.0 technologies that critically enhance dual organizational core values, including well-being and safety. AR and virtualization involve human–computer interaction to distinguish between objects in the virtual and real world (CIDB 2020). Adopting this technology offers designers real-scale visualization, enhances their grasp of design effects, reduces flaws, and ultimately helps professionals manage workloads and stress, promoting well-being in construction (Delgado et al. 2020). Beyond well-being, AR and virtualization exert compelling impacts on construction safety by revolutionizing safety education and training methods (Dobrucali et al. 2022). Therefore, the impacts of AR and virtualization that enhance well-being and safety in construction cannot be overlooked.

Study implication

Theoretical implication

Unlike existing works that primarily focused on enhancing one or two core values, this study stands out by comprehensively evaluating the impact of twelve Construction 4.0 technologies on five organizational core values. Therefore, the study findings deliver a better understanding of making sound decisions in selecting appropriate Construction 4.0 technologies to enhance multiple organizational core values. According to our understanding, this is the first paper that evaluates a list of critical Construction 4.0 technologies for enhancing multiple organizational core values. Furthermore, this study provides a theoretical framework for understanding how the technologies can impact not only sustainability and resiliency but extended to broader spectrums of well-being, productivity, safety, and integrity. Using Construction 4.0 technologies to improve well-being has indirect environmental implications, as healthier environments often correlate with more sustainable practices. Moreover, productivity, safety, and integrity contribute to the environment by reducing waste and accidents, as well as improving the use of resources. Furthermore, integrity ensures compliance with environmental regulations and standards. Hence, this study advances existing works and fills the gap in existing works on both Construction 4.0 technologies and environmental science.

Practical implication

The study findings suggest four critical Construction 4.0 technologies that benefit multiple organizational core values. Thus, industry professionals, particularly top managers, could make informed decisions in selecting Construction 4.0 technologies. They can adopt specific Construction 4.0 technologies to enhance sustainability and resiliency, well-being, productivity, safety, and integrity. In addition, the suggested Construction 4.0 technologies further persuade potential investors to acquire construction 4.0 technologies. Moreover, policymakers may use the findings to develop action plans for accelerating the construction industry's digital transformation. Policymakers may prioritize the action plans based on BIM, IoT, big data and predictive analytics, and autonomous construction as these technologies positively impact multiple organizational core values simultaneously.

Conclusion

Selecting appropriate Construction 4.0 technologies that align with specific organizational core values is challenging. Therefore, this study aims to compare the impact of Construction 4.0 technologies on different organizational core values, focusing on sustainability and resiliency, well-being, productivity, safety, and integrity. To achieve that aim, the study objectives are as follows: (i) identify the critical Construction 4.0 technologies between core values; (ii) appraise overlapping critical Construction 4.0 technologies between core values; (iii) examine the ranking performance of Construction 4.0 technologies between core values; and (iv) analyze the interrelationships between Construction 4.0 technologies and core values.

A fuzzy TOPSIS data collection instrument was developed using a list of Construction 4.0 technologies and an organizational core value list from a national strategic plan. Afterward, fourteen experts from industry and academia were selected and evaluated the Construction 4.0 technologies in enhancing the five organizational core values. Data analysis involved fuzzy TOPSIS and NV. Then, critical overlapping Construction 4.0 technologies were identified through overlap analysis. The established performance indicators, including ρ, τ, RMSE, and AAD, were used to assess ranking performance. Besides, in agreement analysis, the rank agreement factor assessed differences in rankings between core values using a pairwise approach. Finally, Spearman's correlation analyzed the interrelationships between technologies and core values.

The study findings disclosed four critical Construction 4.0 technologies that enhance five organizational core values: BIM, IoT, big data and predictive analytics, and autonomous construction. Meanwhile, cloud and real-time collaboration are critical to enhance three organizational core values: well-being, productivity, and integrity. Then, AR and virtualization is the critical technology that enhances well-being and safety values. The results of agreement analysis reveal that the highest agreement is between "well-being" and "productivity." Finally, most impacts have moderate to strong correlations between different core values. In conclusion, the study findings provide significant insights regarding critical Construction 4.0 technologies that enhance multiple organizational core values.

Limitations and future works

Although the study aim was achieved, the findings do have some limitations. Firstly, the study focused on a list of Construction 4.0 technologies and core values outlined in a national strategic plan. Future works, particularly in regions with differing lists of core values and technologies, can adapt the study design for tailored insights. Secondly, the data collection involved a single country, limiting generalizability due to environmental and cultural differences. Expanding research across multiple countries can reveal variations in judgments. Then, this study involved a limited number of experts due to time limitations. The richness of the findings can be further generalized by increasing the number of experts involved. From a methodological aspect, this study employed fuzzy TOPSIS to achieve the study aim. Future works may use other MCDM approaches, including fuzzy AHP, fuzzy VIKOR, fuzzy PROMETHEE, fuzzy ANP, or other hybrid methods. Additionally, the study findings rely on the subjective judgment of experts. This judgment may not fully reflect the technology's actual performance. Incorporating field experiments in future works can offer more objective assessments. Despite these limitations, the study provides valuable insights into critical Construction 4.0 technologies that enhance organizational core values, benefiting researchers, industry practitioners, and policymakers.

Appendix

Table 7 Experts involved in this study

Expert	Designation	Years of working experience	Experts' background	Educational background	
				Highest education level	Educational discipline
E1	Civil engineer	5 years	Contractor	Master	Building and construction
E2	Civil engineer	21 years	Client	Bachelor	Civil engineering
E3	BIM coordinator	7 years	Consultant	Master	Mechanical
E4	BIM coordinator	9 years	Contractor	Master	Interior designer
E5	Civil engineer	38 years	Consultant	PhD	Civil engineering
E6	Senior lecturer	7 years	Academic	PhD	Civil engineering
E7	Director	8 years	Consultant	Bachelor	Architecture
E8	BIM manager	24 years	Client	Diploma	Architecture
E9	Director	16 years	Consultant	Master	Architecture
E10	BIM manager	6 years	Consultant	Bachelor	Architecture
E11	BIM coordinator	11 years	Consultant	Diploma	Building and construction
E12	Architect	5 years	Contractor	Master	Architecture
E13	Civil engineer	15 years	Consultant	Bachelor	Civil engineering
E14	General manager	18 years	Client	Bachelor	Land surveyor

Table 8 Linguistic terms and TFN for criteria and alternatives

Linguistic terms for criteria	TFN	Linguistic terms for alternatives	TFN
Very low importance (VL)	(1,1,3)	Not important (NI)	(1,1,3)
Low importance (L)	(1,3,5)	Less important (LI)	(1,3,5)
Medium importance (M)	(3,5,7)	Fairly important (FI)	(3,5,7)
High importance (H)	(5,7,9)	Important (I)	(5,7,9)
Very high importance (VH)	(7,9,9)	Very important (VI)	(7,9,9)

TFN, triangular fuzzy numbers

Table 9 Linguistic evaluation for alternatives and the aggregate fuzzy ratings

Core values	Construction 4.0	Experts														Aggregate fuzzy ratings
		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	
Sustainability and resiliency	Big data and predictive analytics	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	LI (1,3,5)	VI (7,9,9)	(1,7.429,9)
	3D scanning and photogrammetry	I (5,7,9)	I (5,7,9)	I (5,7,9)	LI (1,3,5)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	LI (1,3,5)	VI (7,9,9)	(1,6.714,9)
	Advanced building materials	I (5,7,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	VI (7,9,9)	(3,7,9)
	IoT	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	LI (1,3,5)	VI (7,9,9)	(1,7.286,9)
	3D printing and AM	I (5,7,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	LI (1,3,5)	LI (1,3,5)	VI (7,9,9)	LI (1,3,5)	VI (7,9,9)	(1,6.714,9)
	AI	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	LI (1,3,5)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	(1,7,9)
	Cloud and real-time collaboration	FI (3,5,7)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	LI (1,3,5)	FI (3,5,7)	(1,6.714,9)
	Autonomous construction	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	(3,7.143,9)
	AR and virtualization	FI (3,5,7)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	LI (1,3,5)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	(1,6.143,9)
	Blockchain	LI (1,3,5)	I (5,7,9)	I (5,7,9)	(3,5,7)	FI (3,5,7)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	LI (1,3,5)	I (5,7,9)	LI (1,3,5)	LI (1,3,5)	FI (3,5,7)	(1,5.571,9)
	Prefabrication and modular construction	I (5,7,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	LI (1,3,5)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	(1,7.143,9)
	BIM	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	(3,7.571,9)

Table 9 (continued)

Core values	Construction 4.0	Experts														Aggregate fuzzy ratings
		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	
Well-being	Big data and predictive analytics	FI (3,5,7)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	(3,7.429,9)
	3D scanning and photogrammetry	LI (1,3,5)	I (5,7,9)	VI (7,9,9)	LI (1,3,5)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	LI (1,3,5)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	(1,6,9)
	Advanced building materials	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	LI (1,3,5)	VI (7,9,9)	(1,6.571,9)
	IoT	FI (3,5,7)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	(3,7.429,9)
	3D printing and AM	I (5,7,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	LI (1,3,5)	LI (1,3,5)	I (5,7,9)	FI (3,5,7)	NI (1,1,3)	I (5,7,9)	(1,5.286,9)
	AI	I (5,7,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	LI (1,3,5)	FI (3,5,7)	I (5,7,9)	LI (1,3,5)	VI (7,9,9)	(1,6.714,9)
	Cloud and real-time collaboration	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	(3,7.857,9)
	Autonomous construction	FI (3,5,7)	I (5,7,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	(3,6.714,9)
	AR and virtualization	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	I (5,7,9)	(3,6.714,9)
	Blockchain	I (5,7,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	LI (1,3,5)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	VI (7,9,9)	(1,6.143,9)
	Prefabrication and modular construction	I (5,7,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	LI (1,3,5)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	(1,6.714,9)
	BIM	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	(3,7.286,9)

Table 9 (continued)

Core values	Construction 4.0	Experts														Aggregate fuzzy ratings
		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	
Productivity	Big data and predictive analytics	FI (3,5,7)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	(3,7.857,9)
	3D scanning and photogrammetry	FI (3,5,7)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	LI (1,3,5)	VI (7,9,9)	(1,7.286,9)
	Advanced building materials	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	(3,7.143,9)
	IoT	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	(3,7.714,9)
	3D printing and AM	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	LI (1,3,5)	I (5,7,9)	I (5,7,9)	LI (1,3,5)	VI (7,9,9)	(1,6.714,9)
	AI	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	LI (1,3,5)	FI (3,5,7)	VI (7,9,9)	LI (1,3,5)	VI (7,9,9)	(1,7.286,9)
	Cloud and real-time collaboration	FI (3,5,7)	I (5,7,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	(3,7.571,9)
	Autonomous construction	FI (3,5,7)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	(3,7.429,9)
	AR and virtualization	FI (3,5,7)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	(3,7.286,9)
	Blockchain	(1,3,5)	I (5,7,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	LI (1,3,5)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	VI (7,9,9)	(1,6.286,9)
	Prefabrication and modular construction	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	LI (1,3,5)	FI (3,5,7)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	(1,7.857,9)
	BIM	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	(5,8.286,9)

Table 9 (continued)

Core values	Construction 4.0	Experts														Aggregate fuzzy ratings
		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	
Safety	Big data and predictive analytics	LI (1,3,5)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	(1,6.714,9)
	3D scanning and photogrammetry	LI (1,3,5)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	(1,5.714,9)
	Advanced building materials	I (5,7,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	LI (1,3,5)	VI (7,9,9)	(1,6,9)
	IoT	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	(3,6.857,9)
	3D printing and AM	I (5,7,9)	LI (1,3,5)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	LI (1,3,5)	LI (1,3,5)	VI (7,9,9)	LI (1,3,5)	VI (7,9,9)	(1,5.714,9)
	AI	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	LI (1,3,5)	FI (3,5,7)	I (5,7,9)	LI (1,3,5)	I (5,7,9)	(1,6.286,9)
	Cloud and real-time collaboration	LI (1,3,5)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	LI (1,3,5)	VI (7,9,9)	(1,5.857,9)
	Autonomous construction	I (5,7,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	(3,6.571,9)
	AR and virtualization	I (5,7,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	LI (1,3,5)	FI (3,5,7)	(1,6.143,9)
	Blockchain	LI (1,3,5)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	FI (3,5,7)	LI (1,3,5)	LI (1,3,5)	FI (3,5,7)	LI (1,3,5)	FI (3,5,7)	FI (3,5,7)	(1,4.857,9)
	Prefabrication and modular construction	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	LI (1,3,5)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	(1,6,9)
	BIM	LI (1,3,5)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	FI (3,5,7)	(1,6.286,9)

Table 9 (continued)

Core values	Construction 4.0	Experts														Aggregate fuzzy ratings
		E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	
Integrity	Big data and predictive analytics	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	LI (1,3,5)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	FI (3,5,7)	LI (1,3,5)	VI (7,9,9)	(1,6.571,9)
	3D scanning and photogrammetry	LI (1,3,5)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	LI (1,3,5)	VI (7,9,9)	(1,6.286,9)
	Advanced building materials	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	LI (1,3,5)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	LI (1,3,5)	VI (7,9,9)	(1,6,9)
	IoT	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	LI (1,3,5)	VI (7,9,9)	(1,7,9)
	3D printing and AM	I (5,7,9)	LI (1,3,5)	FI (3,5,7)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	LI (1,3,5)	FI (3,5,7)	LI (1,3,5)	LI (1,3,5)	FI (3,5,7)	(1,5.286,9)
	AI	I (5,7,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	LI (1,3,5)	FI (3,5,7)	I (5,7,9)	LI (1,3,5)	FI (3,5,7)	(1,6.286,9)
	Cloud and real-time collaboration	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	FI (3,5,7)	LI (1,3,5)	VI (7,9,9)	(1,7,9)
	Autonomous construction	I (5,7,9)	I (5,7,9)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	I (5,7,9)	FI (3,5,7)	LI (1,3,5)	VI (7,9,9)	(1,6.714,9)
	AR and virtualization	I (5,7,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	LI (1,3,5)	FI (3,5,7)	LI (1,3,5)	VI (7,9,9)	(1,6,9)
	Blockchain	FI (3,5,7)	FI (3,5,7)	FI (3,5,7)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	VI (7,9,9)	FI (3,5,7)	VI (7,9,9)	LI (1,3,5)	FI (3,5,7)	LI (1,3,5)	LI (1,3,5)	VI (7,9,9)	(1,6,9)
	Prefabrication and modular construction	I (5,7,9)	LI (1,3,5)	FI (3,5,7)	I (5,7,9)	I (5,7,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	LI (1,3,5)	FI (3,5,7)	I (5,7,9)	LI (1,3,5)	VI (7,9,9)	(1,6.286,9)
	BIM	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	I (5,7,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	VI (7,9,9)	I (5,7,9)	I (5,7,9)	LI (1,3,5)	VI (7,9,9)	(1,7.857,9)

VI, very important; *I*, important; *FI*, fairly important; *LI*, less important; *NI*, not important

Table 10 Linguistic evaluation for criteria and the aggregate fuzzy weight

Construction 4.0	Experts														Aggregate fuzzy weight
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	
Sustainability and resiliency	H (5,7,9)	VH (7,9,9)	H (5,7,9)	VH (7,9,9)	H (5,7,9)	VH (7,9,9)	H (5,7,9)	H (5,7,9)	VH (7,9,9)	H (5,7,9)	M (3,5,7)	H (5,7,9)	L (1,3,5)	VH (7,9,9)	(1,7.286,9)
Well-being	H (5,7,9)	VH (7,9,9)	VH (7,9,9)	VH (7,9,9)	H (5,7,9)	VH (7,9,9)	H (5,7,9)	H (5,7,9)	VH (7,9,9)	H (5,7,9)	H (5,7,9)	H (5,7,9)	M (3,5,7)	VH (7,9,9)	(3,7.714,9)
Productivity	H (5,7,9)	VH (7,9,9)	VH (7,9,9)	H (5,7,9)	VH (7,9,9)	VH (7,9,9)	H (5,7,9)	VH (7,9,9)	VH (7,9,9)	VH (7,9,9)	VH (7,9,9)	VH (7,9,9)	VH (7,9,9)	VH (7,9,9)	(5,8.571,9)
Safety	VH (7,9,9)	VH (7,9,9)	H (5,7,9)	H (5,7,9)	H (5,7,9)	VH (7,9,9)	H (5,7,9)	H (5,7,9)	VH (7,9,9)	H (5,7,9)	M (3,5,7)	H (5,7,9)	H (5,7,9)	VH (7,9,9)	(3,7.571,9)
Integrity	VH (7,9,9)	VH (7,9,9)	H (5,7,9)	H (5,7,9)	VH (7,9,9)	VH (7,9,9)	H (5,7,9)	VH (7,9,9)	VH (7,9,9)	H (5,7,9)	H (5,7,9)	H (5,7,9)	M (3,5,7)	VH (7,9,9)	(3,7.857,9)

VH, very high importance; *H*, high importance; *M*, medium importance; *L*, low importance; *VL*, very low importance

Table 11 Entropy-based weight for core values (criteria)

Core values	Entropy E_j	Divergent D_j= 1-E_j	Final weight W_j	Rank
Sustainability and resiliency	− 121.1833	122.1833	0.1844	5
Well-being	− 130.1137	131.1137	0.1979	3
Productivity	− 146.1514	147.1514	0.2221	1
Safety	− 127.5989	128.5989	0.1941	4
Integrity	− 132.6286	133.6286	0.2016	2

Table 12 Normalized and weight-normalized fuzzy decision matrix

	Construction 4.0	Sustainability and resiliency	Well-being	Productivity	Safety	Integrity
Normalized fuzzy decision matrix	Big data and predictive analytics	(0.111,0.825,1.000)	(0.333,0.825,1.000)	(0.333,0.873,1.000)	(0.111,0.746,1.000)	(0.111,0.730,1.000)
	3D scanning and photogrammetry	(0.111,0.746,1.000)	(0.111,0.667,1.000)	(0.111,0.810,1.000)	(0.111,0.635,1.000)	(0.111,0.698,1.000)
	Advanced building materials	(0.333,0.778,1.000)	(0.111,0.730,1.000)	(0.333,0.794,1.000)	(0.111,0.667,1.000)	(0.111,0.667,1.000)
	IoT	(0.111,0.810,1.000)	(0.333,0.825,1.000)	(0.333,0.857,1.000)	(0.333,0.762,1.000)	(0.111,0.778,1.000)
	3D printing and AM	(0.111,0.746,1.000)	(0.111,0.587,1.000)	(0.111,0.746,1.000)	(0.111,0.635,1.000)	(0.111,0.587,1.000)
	AI	(0.111,0.778,1.000)	(0.111,0.746,1.000)	(0.111,0.810,1.000)	(0.111,0.698,1.000)	(0.111,0.698,1.000)
	Cloud and real-time collaboration	(0.111,0.746,1.000)	(0.333,0.873,1.000)	(0.333,0.841,1.000)	(0.111,0.651,1.000)	(0.111,0.778,1.000)
	Autonomous construction	(0.333,0.794,1.000)	(0.333,0.746,1.000)	(0.333,0.825,1.000)	(0.333,0.730,1.000)	(0.111,0.746,1.000)
	AR and virtualization	(0.111,0.683,1.000)	(0.333,0.746,1.000)	(0.333,0.810,1.000)	(0.111,0.683,1.000)	(0.111,0.667,1.000)
	Blockchain	(0.111,0.619,1.000)	(0.111,0.683,1.000)	(0.111,0.698,1.000)	(0.111,0.540,1.000)	(0.111,0.667,1.000)
	Prefabrication and modular construction	(0.111,0.794,1.000)	(0.111,0.746,1.000)	(0.111,0.873,1.000)	(0.111,0.667,1.000)	(0.111,0.698,1.000)
	BIM	(0.333,0.841,1.000)	(0.333,0.810,1.000)	(0.556,0.921,1.000)	(0.111,0.698,1.000)	(0.111,0.873,1.000)
Weight-normalized fuzzy decision matrix	Big data and predictive analytics	(0.333,6.485,9.000)	(1.000,6.367,9.000)	(1.667,7.483,9.000)	(0.111,5.435,9.000)	(0.333,5.737,9.000)
	3D scanning and photogrammetry	(0.333,5.862,9.000)	(0.333,5.143,9.000)	(0.556,6.939,9.000)	(0.111,4.626,9.000)	(0.333,5.488,9.000)
	Advanced building materials	(1.000,6.111,9.000)	(0.333,5.633,9.000)	(1.667,6.803,9.000)	(0.111,4.857,9.000)	(0.333,5.238,9.000)
	IoT	(0.333,6.361,9.000)	(1.000,6.367,9.000)	(1.667,7.347,9.000)	(0.333,5.551,9.000)	(0.333,6.111,9.000)
	3D printing and AM	(0.333,5.862,9.000)	(0.333,4.531,9.000)	(0.556,6.395,9.000)	(0.111,4.626,9.000)	(0.333,4.615,9.000)
	AI	(0.333,6.111,9.000)	(0.333,5.755,9.000)	(0.556,6.939,9.000)	(0.111,5.088,9.000)	(0.333,5.488,9.000)
	Cloud and real-time collaboration	(0.333,5.862,9.000)	(1.000,6.735,9.000)	(1.667,7.211,9.000)	(0.111,4.741,9.000)	(0.333,6.111,9.000)
	Autonomous construction	(1.000,6.236,9.000)	(1.000,5.755,9.000)	(1.667,7.075,9.000)	(0.333,5.320,9.000)	(0.333,5.862,9.000)
	AR and virtualization	(0.333,5.363,9.000)	(1.000,5.755,9.000)	(1.667,6.939,9.000)	(0.111,4.973,9.000)	(0.333,5.238,9.000)
	Blockchain	(0.333,4.864,9.000)	(0.333,5.265,9.000)	(0.556,5.986,9.000)	(0.111,3.932,9.000)	(0.333,5.238,9.000)
	Prefabrication and modular construction	(0.333,6.236,9.000)	(0.333,5.755,9.000)	(0.556,7.483,9.000)	(0.111,4.857,9.000)	(0.333,5.488,9.000)
	BIM	(1.000,6.610,9.000)	(1.000,6.245,9.000)	(2.778,7.891,9.000)	(0.111,5.088,9.000)	(0.333,6.859,9.000)

Table 13 Distance from FPIS and FNIS

Construction 4.0	Sustainability and resiliency		Well-being		Productivity		Safety		Integrity	
	FPIS	FNIS	FPIS	FNIS	FPIS	FNIS	FPIS	FNIS	FPIS	FNIS
Big data and predictive analytics	5.210	6.136	4.862	6.109	4.324	6.339	5.529	5.982	5.347	5.897
3D scanning and photogrammetry	5.322	5.935	5.477	5.723	5.019	6.112	5.720	5.756	5.399	5.822
Advanced building materials	4.911	6.026	5.368	5.865	4.420	6.098	5.662	5.818	5.455	5.749
IoT	5.231	6.095	4.862	6.109	4.340	6.289	5.385	6.018	5.274	6.014
3D printing and AM	5.322	5.935	5.630	5.560	5.102	5.927	5.720	5.756	5.608	5.581
AI	5.274	6.014	5.343	5.902	5.019	6.112	5.607	5.882	5.399	5.822
Cloud and real-time collaboration	5.322	5.935	4.800	6.233	4.358	6.241	5.691	5.787	5.274	6.014
Autonomous construction	4.887	6.066	4.984	5.915	4.377	6.193	5.436	5.950	5.322	5.935
AR and virtualization	5.426	5.785	4.984	5.915	4.398	6.145	5.634	5.849	5.455	5.749
Blockchain	5.544	5.646	5.449	5.757	5.177	5.797	5.908	5.586	5.455	5.749
Prefabrication and modular construction	5.252	6.054	5.343	5.902	4.953	6.306	5.662	5.818	5.399	5.822
BIM	4.821	6.190	4.885	6.069	3.649	6.584	5.607	5.882	5.154	6.264

FPIS, fuzzy positive ideal solution; *FNIS*, fuzzy negative ideal solution

Table 14 Percentage agreement of ranking Construction 4.0 technologies

Core values	Sustainability and resiliency	Well-being	Productivity	Safety	Integrity
Sustainability and resiliency	-	32%	55%	59%	46%
Well-being	32%	-	76%	62%	67%
Productivity	55%	76%	-	63%	63%
Safety	59%	62%	63%	-	47%
Integrity	46%	67%	63%	47%	-

Table 15 Sensitivity analysis

Scenario		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Criteria weight		All: (1,1,3)	All: (1,3,5)	All: (3,5,7)	All: (5,7,9)	All: (7,9,9)	C1 (7,9,9) and C2,C3,C4,C5 (1,1,3)	C2 (7,9,9) and C1,C3,C4,C5 (1,1,3)	C3 (7,9,9) and C1,C2,C4,C5 (1,1,3)	C4 (7,9,9) and C1,C2,C3,C5 (1,1,3)	C5 (7,9,9) and C1,C2,C3,C4 (1,1,3)
Ranked Construction 4.0 technologies based on sensitivity analysis	1	BIM	BIM	BIM	BIM	BIM	BIM	BIM	IoT	BIM	BIM
	2	Autonomous construction	IoT	IoT	IoT	Autonomous construction	Cloud and real-time collaboration	IoT	Autonomous construction	Autonomous construction	IoT
	3	IoT	Big data and predictive analytics	Autonomous construction	Autonomous construction	IoT	IoT	Big data and predictive analytics	BIM	Advanced building materials	Autonomous construction
	4	Big data and predictive analytics	Autonomous construction	Big data and predictive analytics	Big data and predictive analytics	Big data and predictive analytics	Big data and predictive analytics	Autonomous construction	Big data and predictive analytics	IoT	Cloud and real-time collaboration
	5	Cloud and real-time collaboration	Cloud and real-time collaboration	Cloud and real-time collaboration	Cloud and real-time collaboration	Cloud and real-time collaboration	Autonomous construction	Cloud and real-time collaboration	Cloud and real-time collaboration	Big data and predictive analytics	Big data and predictive analytics
	6	Advanced building materials	Advanced building materials	Advanced building materials	Advanced building materials	Advanced building materials	AR and virtualization	AR and virtualization	AR and virtualization	Cloud and real-time collaboration	Advanced building materials
	7	AR and virtualization	Prefabrication and modular construction	AR and virtualization	AR and virtualization	AR and virtualization	Advanced building materials	Advanced building materials	Advanced building materials	Prefabrication and modular construction	Prefabrication and modular construction
	8	Prefabrication and modular construction	AR and virtualization	Prefabrication and modular construction	Prefabrication and modular construction	Prefabrication and modular construction	Prefabrication and modular construction	Prefabrication and modular construction	AI	AI	AR and virtualization
	9	AI	AI	AI	AI	AI	AI	AI	Prefabrication and modular construction	3D scanning and photogrammetry	AI
	10	3D scanning and photogrammetry	3D scanning and photogrammetry	3D scanning and photogrammetry	3D scanning and photogrammetry	3D scanning and photogrammetry	3D scanning and photogrammetry	3D scanning and photogrammetry	3D scanning and photogrammetry	AR and virtualization	3D scanning and photogrammetry
	11	3D printing and AM	3D printing and AM	3D printing and AM	3D printing and AM	3D printing and AM	Blockchain	3D printing and AM	3D printing and AM	3D printing and AM	Blockchain
	12	Blockchain	Blockchain	Blockchain	Blockchain	Blockchain	3D printing and AM	Blockchain	Blockchain	Blockchain	3D printing and AM

Table 16 Ranking performance comparison based on sensitivity analysis scenario

Rank performance metric	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
ρ	0.979	0.993	0.993	0.993	0.979	0.944	0.993	0.951	0.881	0.965
τ	0.939	1.000	0.971	0.971	0.939	0.848	1.000	0.848	0.768	0.881
RMSE	0.707	0.408	0.408	0.408	0.707	1.154	0.408	1.080	1.683	0.913
AAD	0.333	0.167	0.167	0.167	0.333	0.833	0.167	0.8333	1.333	0.667

ρ is Spearman's rank correlation coefficient; τ is Kendall's Tau coefficient; RMSE is root mean square error; AAD is average absolute distance

Table 17 Spearman's correlation (ρ) for core values of various Construction 4.0 technologies

Construction 4.0	Core values	Well-being	Productivity	Safety	Sustainability and resiliency	Integrity
Big data and predictive analytics	Well-being	1.000	0.705**	0.492	0.541*	0.346
	Productivity		1.000	0.437	0.558*	0.560*
	Safety			1.000	0.508	0.474
	Sustainability and resiliency				1.000	0.547*
	Integrity					1.000
3D scanning and photogrammetry	Well-being	1.000	0.306	0.383	0.103	0.107
	Productivity		1.000	0.361	0.627*	0.708**
	Safety			1.000	-0.337	0.139
	Sustainability and resiliency					0.742**
	Integrity					1.000
Advanced building materials	Well-being	1.000	***0.867*****	0.699**	0.799**	0.648*
	Productivity		1.000	0.570*	***0.844*****	0.608*
	Safety			1.000	0.602*	0.378
	Sustainability and resiliency				1.000	0.783**
	Integrity					1.000
IoT	Well-being	1.000	0.460	0.358	0.735**	0.455
	Productivity		1.000	0.349	0.409	0.388
	Safety			1.000	0.526	***0.818*****
	Sustainability and resiliency				1.000	0.793**
	Integrity					1.000
3D printing and AM	Well-being	1.000	-0.115	-0.036	-0.309	-0.206
	Productivity		1.000	0.424	0.663**	0.475
	Safety			1.000	0.719**	0.373
	Sustainability and resiliency				1.000	0.479
	Integrity					1.000
AI	Well-being	1.000	***0.844*****	***0.874*****	***0.860*****	0.537*
	Productivity		1.000	***0.840*****	***0.869*****	0.699**
	Safety			1.000	0.749**	0.667**
	Sustainability and resiliency				1.000	0.625*
	Integrity					1.000
Cloud and real-time collaboration	Well-being	1.000	***0.877*****	0.514	0.385	0.403
	Productivity		1.000	0.667**	0.301	0.614*
	Safety			1.000	0.401	0.640*
	Sustainability and resiliency				1.000	0.525
	Integrity					1.000

Table 17 (continued)

Construction 4.0	Core values	Well-being	Productivity	Safety	Sustainability and resiliency	Integrity
Autonomous construction	Well-being	1.000	0.744**	0.571*	0.231	0.226
	Productivity		1.000	0.574*	0.452	0.445
	Safety			1.000	0.326	0.500
	Sustainability and resiliency				1.000	0.489
	Integrity					1.000
AR and virtualization	Well-being	1.000	0.717**	0.504	0.661*	0.550*
	Productivity		1.000	0.498	0.561*	0.463
	Safety			1.000	0.434	0.399
	Sustainability and resiliency				1.000	0.620*
	Integrity					1.000
Blockchain	Well-being	1.000	0.697**	0.297	0.594*	0.612*
	Productivity		1.000	0.462	***0.820***	0.791**
	Safety			1.000	0.498	0.476
	Sustainability and resiliency				1.000	0.678**
	Integrity					1.000
Prefabrication and modular construction	Well-being	1.000	0.440	0.265	***0.807***	0.182
	Productivity		1.000	0.361	0.460	0.155
	Safety			1.000	0.196	0.401
	Sustainability and resiliency				1.000	0.304
	Integrity					1.000
BIM	Well-being	1.000	0.159	0.335	0.487	0.034
	Productivity		1.000	0.158	0.081	0.189
	Safety			1.000	0.307	0.508
	Sustainability and resiliency				1.000	0.452
	Integrity					1.000

Values in *italics* and **bold** with asterisks indicate a “very strong correlation” between Construction 4.0 technologies

*Construction 4.0 with a correlation significant at the 0.05 level (two-tailed); **Construction 4.0 with a correlation significant at the 0.01 level (two-tailed)

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Data availability Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions (e.g., anonymized data).

Declarations

Ethical approval Ethical approval and informed consent are not applicable to this study.

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We confirmed that this manuscript has not been published elsewhere and is not under consideration by another journal.