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Digital twin-enabled synchronized construction management: A roadmap from construction 4.0 towards future prospect

Yishuo Jiang [a,b], Shuaiming Su [a], Shuxuan Zhao [a], Ray Y. Zhong [a,*], Waishan Qiu [c], Miroslaw J. Skibniewski [d], Ioannis Brilakis [e], George Q. Huang [f]

[a] Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, China
[b] Department of Systems Engineering, Cornell University, USA
[c] Department of Urban Planning and Design, The University of Hong Kong, China
[d] Department of Civil and Environmental Engineering, University of Maryland, College Park, USA
[e] Department of Engineering, University of Cambridge, United Kingdom
[f] Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, China

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ABSTRACT

Information and automation technologies play a pivotal role in achieving cyber-physical integration within Construction 4.0. In this transformed landscape, the evolution of the construction management paradigm carefully considers the enhancement of business models and organizational structures to prioritize stakeholders' well-being, environmental sustainability, and heightened resilience. A significant challenge lies in effectively managing and coordinating a myriad of multi-source and heterogeneous entities using information and automation technologies. The key obstacle is synchronizing these elements based on cyber-physical interoperation to optimize multiple objectives seamlessly. Hence synchronization emerges as a crucial factor for orchestrating and sustaining harmonious relationships among multiple entities or activities within a delimited spatial-temporal framework. This ensures seamless and aligned coordination throughout dynamic processes. Therefore, this paper presents a strategic roadmap for the synchronized construction management, derived from a thorough analysis of fundamental elements in Construction 4.0, aimed at advancing the current construction management practices. Moreover, to articulate this synchronization approach systematically, an Orthogonally Synchronized Digital Twin (SDT) model with regular expression is formulated, built upon the proposed roadmap for reshaped construction management. This study provides valuable insights for stakeholders in the construction industry, including architects, engineers, project managers, and policymakers. The findings guide decision-making on digital twin adoption in construction, supporting practitioners to enhance efficiency and improve outcomes, offering a roadmap for industry advancement towards human-centrality, sustainability, and resilience. Future research should focus on validating the proposed roadmap and SDT model in real-world scenarios, exploring synergies between AI and digital twins, and investigating advanced technologies for holistic smart cities management.

1. Introduction

Multiple cutting-edge technologies are applied to reshape construction industry and converts it into cyber-physical construction integrated with various digital twins, which form the profile of Construction 4.0 era (F. Jiang et al., 2021; Sacks et al., 2020). Physical construction resources and their respective digital twins are amalgamated and interoperated in the real-time basis, thus capitalizing on the advantages of real-time decentralized decision-making in construction planning, scheduling, and execution management (Guo et al., 2020; Li et al., 2021). This paradigm shifts towards Construction 4.0 not only enhances productivity but also opens gates to new levels of innovation and sustainability within the industry.

In the context of construction 4.0, construction management rapidly moves towards three trends, including digitalization, automation, and intelligence (El Jazzar et al., 2021; Hossain et al., 2019). The definitions of the three trends are presented as follows.

* Corresponding author.
E-mail address: zhongzry@hku.hk (R.Y. Zhong).

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- **Digitalization**: Digitalization is achieved through the integration of real-time multi-dimensional data, updated by the Internet of Things (IoT), with traditional Building Information Modeling (BIM) (Agapaki et al., 2018; Chen et al., 2015; Wu et al., 2023). It allows stakeholders to monitor real-time resource status and construction progress through IoT-enabled BIM. Information is shared among all users via cloud computing, facilitating collaborative decision-making about operations and material supply based on real-time data (Chen et al., 2017; Dikmen et al., 2022; Niu et al., 2017).
- **Automation**: Construction automation is primarily driven by prefabrication, transitioning from conventional cast-in-situ methods to manufacturing prefabricated components in off-site factories and assembling them on-site (X. Li et al., 2018). This industrialized construction process forms a standard workflow, making it easier to achieve automatic planning and scheduling of operations management both in off-site production and on-site assembly (Xu et al., 2018). Additionally, this controlled environment is conducive to the application of robotic technologies for automated manufacturing and assembly of prefabricated components during the execution phase.
- **Intelligence**: Intelligence is pivotal in Construction 4.0, with machine learning, data mining, and knowledge-based analytics anticipating variables in construction projects. Simulating activities proactively addresses challenges and optimizes performance indicators. Continuous refinement of machine learning and data mining enhances decision-making, fostering adaptability. This data-driven intelligence ensures an optimized construction management process in line with Construction 4.0 principles (Hong et al., 2022).

Construction 4.0 is developed by the foundational principles of Industry 4.0 (Turner et al., 2021). As the rapid development of technologies, Industry 5.0 has been proposed in recent years. In a similar way, Industry 5.0 is a thoughtful concept considering the future of the industry as a manufacturing/production system that is human-centric, sustainable, and resilient (Maddikunta et al., 2022). The current understanding of Industry 5.0 is to place the well-being of workers at the center of the manufacturing process, which also entails the incorporation of artificial intelligence into human operations to enhance man's capacity (Leng et al., 2022). The core principle of Industry 5.0 is the harmony among humans, machines, values, tasks, and services. Similarly, extended from 4.0 era and inspired by Industry 5.0, future construction pays more attention to achieve a more efficient, sustainable, and human-centric construction industry through information and automation technologies. The principal goals are set to realize more efficient designs and operations, save more resources to reduce environmental and social impact (Li et al., 2023), as well as improve the productivity and competitiveness of the entire industry (Marinelli, 2023). For future construction management mode, it is not only an application of technologies under cyber-physical integrated context. The reshaped management fully considers the upgrading of business model and organizational structure for stakeholder-worker wellbeing, as well as promoting collaboration and cooperation in various stages (e.g., design, construction, operation, and maintenance). Environmental sustainability is also fully considered for the multi-domain balance and improved resilience for unexpected disruptions in stochastic circumstances.

For the research motivations, a significant challenge lies in effectively managing and coordinating a myriad of multi-source and heterogeneous entities, including humans, machines, materials, energy, and value. The key obstacle is harmonizing and synchronizing these elements to optimize multiple objectives seamlessly. Specifically, diverse entities involved in a construction project, such as governments, enterprises, academia, and social organizations, need advanced collaboration mechanisms. This involves translating various business goals into integrated actionable plans to balance the interests of different stakeholders effectively. A key motivation is to establish a cyber-physical integration environment capable of providing optimized solutions within an acceptable computational time frame. Establishing this advanced environment is pivotal to foster harmonious coexistence and effective interaction among humans, machines, and their surroundings in the construction industry (Albini et al., 2023). Towards future construction, there is still a long way to explore, where key scientific questions, new methods, and implementation tests should be investigated.

This paper proposes the core concept of future construction management is the digital twin-enabled orthogonal synchronization. In natural science, synchronization refers to "the adjustment of rhythms due to interaction" (Glass, 2001). In engineering management, synchronization refers to the coordination and maintenance of a certain relative relationship between multiple objects or activities within a limited spatial-temporal scope. It ensures that these objects or activities remain connected and aligned during their changing processes. After analytics about the current research status, two research gaps are supposed to be solved.

- ***Research Gap 1***: While Construction 4.0 acknowledges several key technologies for achieving digitalization, automation, and intelligence, its main focuses and refined key factors on associated domain problems remain obscure. Construction 4.0 operates within the engineering domain, borrowing advanced technologies for interdisciplinary applications. Therefore, the construction industry should emphasize domain problems and refined key technological or domain factors rather than the transplanted technologies themselves. Future efforts should enhance the identification of specific aspects and concretized factors in the construction area. A strategic plan is crucial to systematically organize these technologies and endeavors. Thus, a systematic roadmap is needed to reveal the prospect of the construction management mode.
- ***Research Gap 2***: Digital twin or CPS is generally recognized as the core element in Construction 4.0, similar to the proposal in Industry 4.0. However, when compared with the manufacturing industry, the construction site is more uncertain and unstable due to outdoor conditions. The workflow is challenging to standardize and predict, given the numerous multi-source and heterogeneous resources involved. The organizational structure and administrative mode in construction projects are also more complicated. Therefore, there is a need to research how to use digital twins to achieve a closed-loop synchronized environment with interconnected multi-level, multi-source, and heterogeneous objects in such a highly uncertain and complex setting. Concrete descriptive or mechanism models are currently absent, hindering the ability to provide a more scientific and logical landscape for future construction. Mathematical regular expressions hold value in systematically unveiling the managerial mechanism of the digital twin-based new managerial mode. Further research is essential to establish precise models and expressions that contribute to a comprehensive understanding and implementation of advanced construction methodologies.

The research objectives of this paper encompass two crucial aspects: (1) To propose a practical roadmap for the future of construction management. This roadmap is designed to guide the integration of new technologies within a cyber-physical framework, emphasizing a comprehensive and strategic approach to construction practices. The roadmap considers the changing landscape of construction, with a focus on stakeholder-worker well-being, environmental sustainability, and resilience to unforeseen disruptions in uncertain environments. (2) To introduce a regular expression model that constitutes the core of future construction management mechanism. By employing a standardized mathematical language and rigorous logic, this model aims to provide a clear framework for comprehending the intricacies of smart construction management in the future. The conceptual core of the proposed model lies in digital twin-enabled orthogonal synchronization, representing a pivotal attribute for future management. This model involves both vertical-dimensional cyber-physical synchronization and horizontal-dimensional domain synchronization. Vertical level focuses on achieving real-time bidirectional interoperation between physical and digital spaces. Horizontal level coordinates interactions among different construction resources, operations, humans, and energy. Hence, industrial professionals and scholars could be assisted to gain a better understanding of the internal core mechanisms of future intelligent construction management.

The rest of this paper is organized as follows. Section 2 introduces the methodology of an adjusted Systematic Literature Review (SLR). Section 3 introduces the foundational analysis of Construction 4.0. Section 4 presents the roadmap towards future construction management with a synchronized digital twin model. Section 5 summarizes the related information techniques as well as a blueprint for future construction paradigm. Section 6 is a final remark and limitation analysis of this review study.

2. Methodology

The review methodology of this paper is Systematic Literature Review (SLR) supported by more discussions and analysis (Grimshaw and Russell, 1993). The adjusted SLR methodology mainly contains the four steps, as shown in Fig. 1.

Step 1: Define key research question (RQ).

Defining the key research question stands as the foundational and imperative step in both the traditional SLR and the contemporary adjusted methodology. The key research question in this paper focuses on *what's the prospect of future construction management*. The cutting-edge technologies emerging from the Construction 4.0 era have the potential to significantly reshape the management paradigm. The domain of engineering problems converges specifically on construction management, rather than encompassing a broader and more dispersed range of issues, such as construction design or maintenance. This approach enables more concentrated reviews, analyses, and discussions.

Step 2: Analyze current research state following systematic strategy.

Step 2 involves carefully formulating the search strategy in strict adherence to the original SLR guidelines. This step is crucial in establishing a solid foundation for exploring the technical environment discussed in this paper, which centers on Construction 4.0. Digital Twin is set as the core element of Construction 4.0, which is conceptualized as an integrated technical environment for future construction management. Industry 4.0 provides the motivation and inspiration for the technical environment, along with novel ideas driving the evolution of the construction industry. Digitalization, automation, and intelligence are the three key domains for this research. The key review rules, adhering to the principles of SLR, are established as follows. For the literature sources, Web of Science (WoS) and Scopus serve as the databases. Inclusion and exclusion criteria involve relevance and timespan as three selection criteria. (a) Relevance is determined through combined keyword searches. Solo keywords include digital twin, Construction 4.0, construction management, technology domains, and engineering domains. (b) Regarding timespan, as Construction 4.0 and the digital twin are relatively recent concepts within the past 10 years, references related to these keywords are selected within the publication date range from 2015 to 2023. However, for foundational information technologies like IoT and computer vision, which form the basis for digital twin and Construction 4.0, the publication date is extended to the range from 2010 to 2023.

Step 3: Systematic analysis and discussion.

Step 3 is modified according to the framework of SLR to incorporate more extensive discussions about the identified problems. Upon obtaining the literature database, the process involves conducting

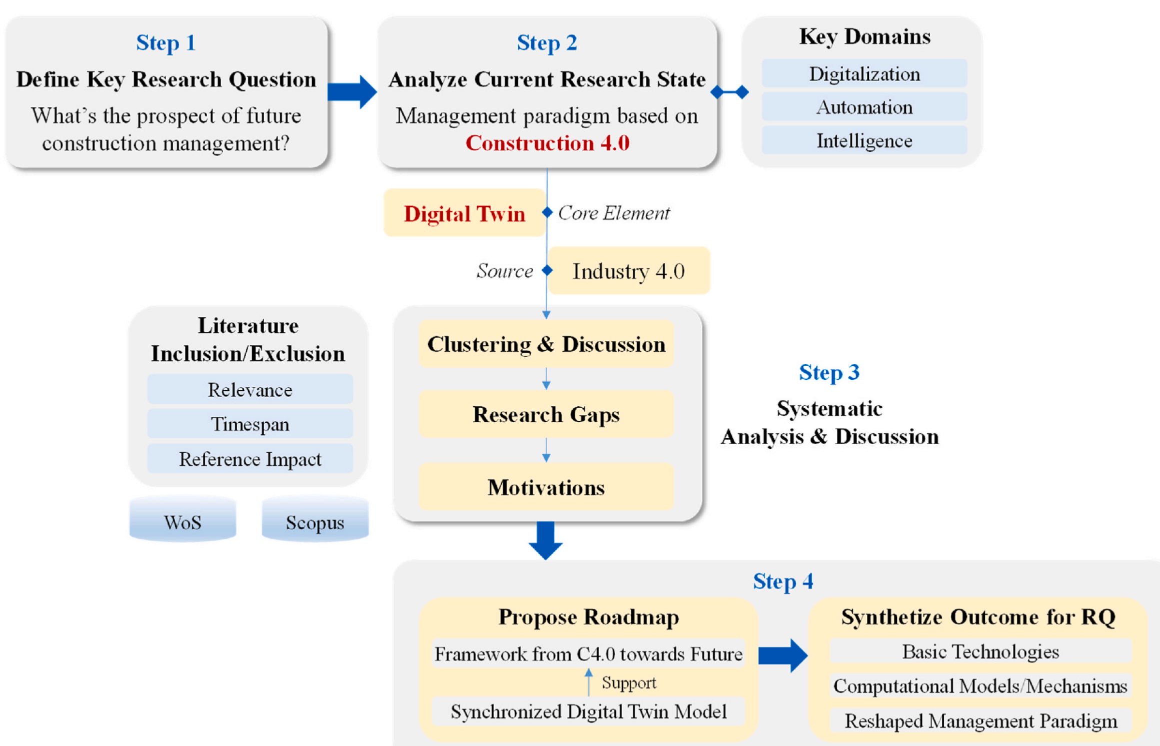

Fig. 1. Methodology based on adjusted systematic literature review (SLR).

clustering and in-depth analysis. Subsequent to these steps, the objective is to extract valuable insights, present a comprehensive summary of existing research outcomes, pinpoint potential challenges or issues, and offer logical and well-reasoned suggestions in a systematic manner. A transition link is applied to connect current research state and future prospect, including clustering, discussion, research gap, and motivation. (a) For clustering, various domains are classified both at the technical and problem levels based on a logical structure. For instance, information and automation technologies are grouped into specific domains such as IoT, robotics, and big data. (b) In the discussion section, this paper delves into the characteristics of keywords, such as Construction 4.0 and digital twin. Several comparisons involving related concepts are also conducted to provide insights for future researchers. (c) Research gaps are identified to unveil the current challenges within the research landscape, and motivations are outlined to pave the way for future research. Both sections 3 and 4 play pivotal roles in establishing logical connections between management in Construction 4.0 and the associated future paradigm.

Step 4: Propose roadmap and synthetize outcome for research question.

In this phase, the objective is to formulate a research roadmap tailored to the specific research question, with a focus on broader applicability across diverse research domains. This step is also an extension of the traditional SLR framework, providing a structured plan to effectively address the research question. (a) Research roadmap design: The research roadmap is crafted with flexibility in mind, making it adaptable to a wide range of research questions and areas. It systematically outlines the key steps, stages, and methodologies required to investigate the research question thoroughly. By tailoring this roadmap to the specific question, it serves as a versatile guide for researchers to follow in their inquiry. (b) Utilization of regular expression: In addition to the roadmap, this phase explores the potential use of regular expression as tools to enhance understanding and analysis. These models can be customized to align with the unique characteristics of the research question, facilitating the structured exploration of complex topics. (c) Synthesis of research outcomes: The synthesis process involves consolidating findings from the systematic literature review and analysis. Researchers aim to provide a comprehensive summary of existing research outcomes, emphasizing common themes, trends, gaps, and opportunities for future investigations. This synthesis contributes to the development of a knowledge base that can guide future research endeavors in a well-organized manner.

3. Foundational analytics for construction 4.0

Construction 4.0 contributes three fundamental elements, namely digitization, automation, and intelligence, and multiple information and automation technologies that pave the way for future construction.

3.1. Definition of construction 4.0

Construction 4.0 is a proposed term in recent 10 years influenced by the foundational principles of Industry 4.0 (Turner et al., 2021). Industry 4.0 aims at establishing smart factories where manufacturing technologies are upgraded and transformed by advanced information and automation technologies, such as Cyber-Physical System (CPS), Internet-of-Things (IoT), robotics, computer vision, and Artificial Intelligence (AI) (X. Liu et al., 2021; Pal et al., 2023; Z. Pan et al., 2022; X. Wu et al., 2022; Yilmaz et al., 2023). In the framework of Industry 4.0, manufacturing systems achieve the real-time monitoring of resources (e.g., operators, machines, and materials) and the production progress, backed by data derived from sensing technologies (Ma et al., 2022; Zhong et al., 2017). Meanwhile, all the real-time data about object status, production task, and project progress are decentralized and shared among all the stakeholders using blockchain and cloud computing (Jiang et al., 2023; Kang et al., 2022; L. Wu et al., 2022).

Similar to the Industry 4.0 paradigm, Construction 4.0 integrates Cyber-Physical Systems (CPS), Internet of Things (IoT), Artificial Intelligence (AI), and robotics to seamlessly connect the digital and physical realms. This integration encompasses BIM along with diverse semantic and geometric data. The result is the establishment of a real-time cyber-physical system spanning the entire lifecycle of construction projects, encompassing planning, design, construction, maintenance, and operation phases (Chen et al., 2022). The driving force behind Construction 4.0 is prominently embodied by the concept of digital twin. This pivotal notion seamlessly integrates state-of-the-art technologies, acting as the bridge that links the physical and digital realms. This transition signifies a paradigm shift from the information era towards a domain characterized by cyber-physical integration and interoperation. The network depicting keywords related to Construction 4.0 is delineated in Fig. 2, with statistical analyses from Web of Science presented in Fig. 3. Noteworthy scholarly contributions have extensively explored the definition, essence, and key technologies underpinning Construction 4.0. Some studies have introduced holistic frameworks, dissecting specific aspects of its influence, while others have concentrated on the intricate techniques associated with Construction 4.0. For a systematic analysis, Table 1 serves as a comprehensive repository, summarizing key research endeavors in the domain of Construction 4.0.

Building upon the analysis of previous papers on Construction 4.0 presented in Table 1, this study delves into several common characteristics in the subsequent Section 3.2.

3.2. Key characteristics of construction 4.0 with digital twins

Three pivotal characteristics of Construction 4.0 are distilled from the existing research landscape, encompassing source/basis (derived from Industry 4.0), primary technological domains (such as digitalization, automation, and intelligence), and the core element (Digital Twin/Cyber-Physical Systems).

(1) **Source and Basis**: Construction 4.0 draws inspirations and foundations from Industry 4.0, both at the conceptual and technological levels. Conceptually, Construction 4.0 aligns with Industry 4.0 in recognizing the significance of digitalization, automation, and intelligence in the construction domain. At the technological level, Construction 4.0 incorporates technologies from Industry 4.0, including IoT, robotics, and 3D printing.
(2) **Main Technological Domains**: The technologies within Construction 4.0 are primarily categorized into three domains: digitalization, automation, and construction mode transformation. Digitalization in construction establishes a foundational step for Construction 4.0, enabling efficient information updating, processing, and sharing. This is supported by Industry 4.0 technologies like IoT and computer vision. Construction automation is chiefly realized through robotics, whether on construction sites or in factories. However, automation in construction progresses more slowly due to the intricate operational processes and unstable working environments, distinguishing it from the manufacturing industry. To further achieve automation, construction mode transformation is widely studies such as 3D printing or additive manufacturing, altering the fundamental processes of building. While this new mode is more amenable to automation, a current limitation is the applicability of 3D printing in the construction of high-rise and large-scale buildings. Intelligence in Construction 4.0 is data-driven and science-informed model or algorithm embedded in terminals or computing centers. Advanced analytics, machine learning, and artificial intelligence are leveraged to analyze vast amounts of data generated from construction projects. This enables predictive maintenance, optimized resource allocation, and improved

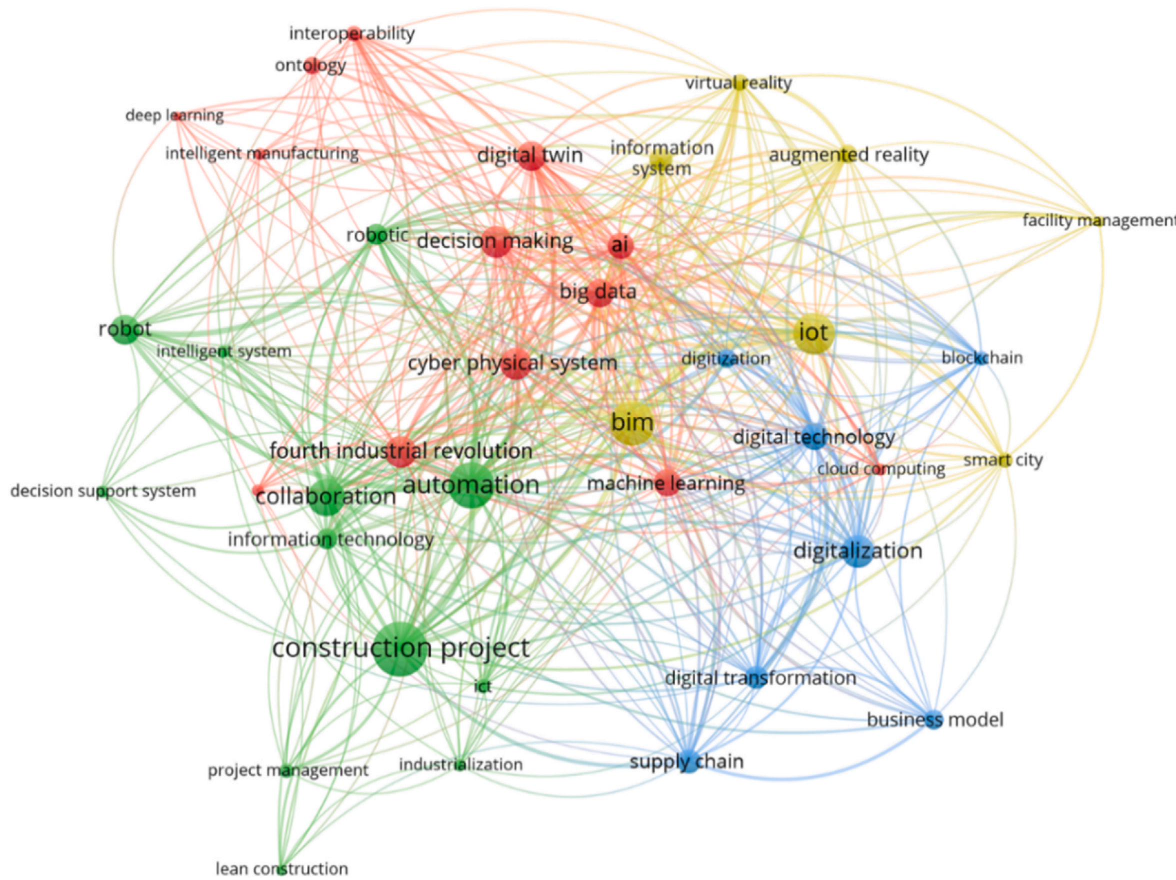

Fig. 2. Network visualization of research keywords about Construction 4.0 (Input keyword: **Construction 4.0**, Scope: from 2010/01/01 to 2023/05/31).

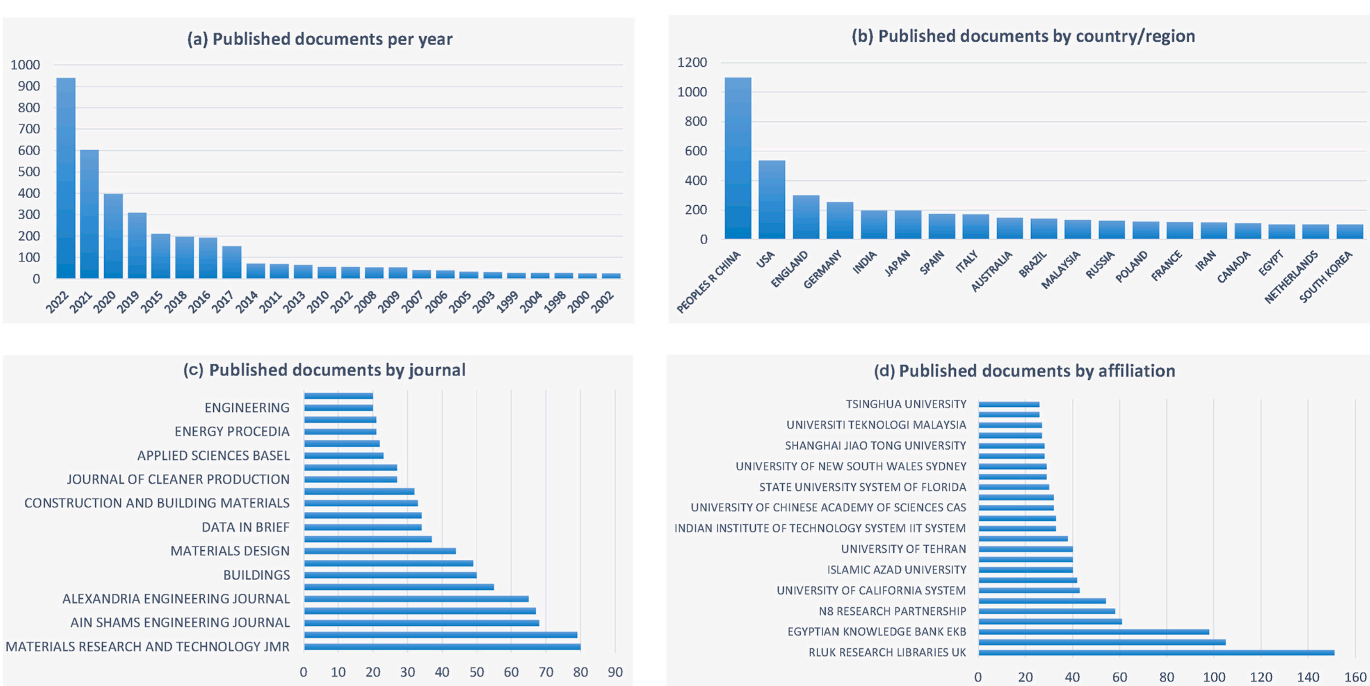

Fig. 3. Statistics about Construction 4.0 from Web of Science (Input: Construction 4.0). (a) Published documents per year; (b) Published documents by country/region; (c) Published documents by journal; and (d) Published documents by affiliation.

Table 1
Analysis of Construction 4.0 in previous studies.

Definition or Essences	Key Contributions	Motivations	Sources
Construction 4.0 is a paradigm that uses CPS, IoT, Data, and Services to link the digital layer consisting of BIM/CDE and physical layer with its whole life to create an interconnected environment integrating organizations, processes, and information.	(1) C4.0 framework based on I4.0 with implementation benefits and barriers. (2) Roles of BIM and CDE in C4.0	(1) To solve the existing horizontal, vertical, and longitudinal fragmentation in construction. (2) To take a comprehensive approach to the improvements needed in the construction industry.	A Proposed Framework for Construction 4.0 Based on a Review of Literature
Construction 4.0's essence is the digitalization and automation in Architecture, Engineering, and Construction (AEC).	(1) Transformation and evolution of organizational structures of construction companies under the fast development of automation technologies. (2) Human-robot collaboration paradigm through digital fabrication.	(1) To address the concern about the future of jobs and wages will increase because of the development of robots. (2) To find the way how the robots and construction workers co-exist.	Implications of Construction 4.0 to the Workforce and Organizational Structures (Mansour et al., 2021)
Transformation of the construction industry towards Industry 4.0, from automated production to a greater level of digitalization, through a BIM system connecting virtual and actual real building.	(1) Construction 4.0 environment enabled by intensive use of different digital and automation technologies, where 3D printing and robot are the pivotal elements. (2) Application scenario of Additive Manufacturing with advanced materials based on digitization technologies to build low-storey construction.	(1) Compared with other industries, construction has been slow to adopt new technologies and has never undergone a major disruptive transformation. (2) Digital transformation will enable construction companies to improve productivity, reduce project delays/ cost, manage complexity, and enhance safety, quality, and resource-efficiency.	Additive manufacturing as an enabling technology for digital construction: A perspective on Construction 4.0 (Craveiro et al., 2019)
A current trend of technology automation and data exchange, which includes CPSs, IoT, cloud computing, cognitive computing and developing smart businesses in the AEC industry.	(1) Explores how the technologies work collaboratively to real-timely integrate data through the interplay of the optimization and simulation. (2) Propose a framework for the next level of DT involving process automation and control towards Construction 4.0 in different project phases.	(1) No insufficient deep learning applications in the digital twin industry. (2) BIM is beneficial but insufficient, and the AEC sector needs something more substantial	An investigation for integration of deep learning and digital twins towards Construction 4.0 (Kor et al., 2022)
Construction 4.0 is an innovative construction management technique propelled by industry 4.0 technologies that allow the creation of a smart construction site.	(1) The findings reveals that the construction professionals are willing to adopt Construction 4.0 technologies for construction project. (2) The finding also reveals that the possibility of fully integrating the technologies into construction is low because the major technologies are rated as not important by the construction professionals.	(1) Challenges of implementing Construction 4.0 technologies range from financial, economic and feasibility perspectives. (2) Construction 4.0 is a vision for the future that will require political and social acceptance. (3) High cost of maintaining the technology, low technical know-how of the professionals and low investment in research related to construction	Appraisal of stakeholders' willingness to adopt construction 4.0 technologies for construction projects (Osunsanmi et al., 2020)
Construction 4.0 is a "transformative framework" where 3 transformations take place: industrial production and construction, cyber-physical systems, and digital technologies.	(1) Identifying 7 key topics (e.g., IoT, 3D printing) through a systematized review considering numerous recent publications. (2) Identifying 3 concrete aspects of challenges (e.g., automation, buildings, dematerialization, and interdisciplinary nature)	Construction 4.0 is developed primarily based on the awareness by construction firms of the digitization of the construction industry and embraced four key concepts: digital data, automation, connectivity, and digital access.	Construction 4.0: A Literature Review (Forcael et al., 2020)
Construction 4.0 is set to be driven by data creation, data flow, data transformation, and data storage across the project lifecycle to ensure a collaborative environment across the stakeholders who interact and associate with different layers of Construction 4.0.	Discussing the possibility of C4.0's design principles aligned to construction project management through the people, process, and technology framework.	(1) The advancements in the use and adoption of Industry 4.0 technology are considerably laggard in the construction sector. (2) Construction industry experiences significant fragmentation in various dimensions that serve as barriers to innovation.	Construction 4.0: what we know and where we are headed? (Karmakar and Delhi, 2021)
Construction 4.0 is the integration of Industry 4.0 to the construction industry.	A multi-criteria decision-making model, named ConFIRM, to measure the strategic readiness of construction firms concerning Industry 4.0 implementation	Industry 4.0 has become a disruptive wave of change that affects the construction industry in many ways.	Implementing industry 4.0 in the construction industry- strategic readiness perspective (Mansour et al., 2021)
Construction 4.0 as digitization and industrialization that 1) enable real-time, horizontal, and vertical integration of stakeholders, 2) promote the advancement of construction processes by employing mechanization and automation, and 3) bridge the gap between physical and cyber spaces.	(1) Proposing four layers of Construction 4.0 implementation plan. (2) A case study where Construction 4.0 technologies act as a crosslinked system is presented to evaluate the 4-layer plan.	Industry 4.0 and the digital transformation at its helm are pushing industries worldwide to embrace newer technologies to continue to remain competitive.	Integrating Construction 4.0 Technologies: A Four-Layer Implementation Plan (El Jazzar et al., 2021)
Construction 4.0 is a new evolving state of construction practice which entails a revolution that incorporates digitalization in construction.	Fulfilment of C4.0 emerged from lean six sigma, value identification and mapping of value stream for crucial adoption of the lean concept to create value for end-users in Construction 4.0 based on structured	Lean thinking about eliminating waste and maintaining quality combined with the technologies from Industry 4.0 to change construction area.	Lean Thinking and Industrial 4.0 Approach to Achieving Construction 4.0 for Industrialization and Technological Development (Lekan et al., 2020)

(continued on next page)

Table 1 (*continued*)

Definition or Essences	Key Contributions	Motivations	Sources
	questionnaire designed in a Likert scale of 1–5 distributed to 100 construction professionals.		
Construction 4.0 is in integration of smart and digital technologies (SDT) with traditional AEC based on lean management principals, as well as the ideas and technical foundation of Industry 4.0.	(1) An overview on Lean Construction 4.0 and raises questions and concerns related to the adoption of Industry 4.0. (2) Three key elements for the implementation of lean construction 4.0, including culture, philosophy, and technology for both academic and industry.	(1) Lean Construction should embrace the changes propelled by Industry 4.0 but maintain the people-processes-technology triad at its core. (2) Construction is falling short in applying the core principles of Industry 4.0, as a coherent, comprehensive, autonomous, decentralized and fully coordinated system is still missing	Lean construction 4.0: exploring the challenges of development in the AEC industry (Hamzeh et al., 2021)

decision-making based on insights derived from data. Intelligence not only enhances project efficiency but also contributes to environmental sustainability and improved safety outcomes.

(3) **Core Element**: The core element of Construction 4.0 is the digital twin or Cyber-Physical Systems (CPS), facilitating real-time integration between the physical and digital spaces at both resource and progress levels (Su et al., 2022; Ye et al., 2023). The concept of the digital twin originated in 2003 when Grieves introduced it for product lifecycle management, consisting of physical product, virtual product, and their connections (Grieves, 2014). Revisited by NASA in 2012, digital twin represents the state of a corresponding entity based on historical data, real-time sensor data, and a physical twin. Described by Gabor, digital twin is a specialized simulation constructed with expert knowledge and real data, achieving more accurate simulations across different scales of time and space (Gabor et al., 2016). According to Maurer, digital twin is a representation that depicts production processes and product performance (Maurer, 2017). While CPS and digital twin share conceptual commonalities, their emphases diverge. CPS emphasizes the 3C concept (computing, communication, and control), while digital twins prioritize the data and models for real-time interoperation between physical entities and their virtual counterparts (Jiang et al., 2023; Tao et al., 2019).

The concept of digital twin is characterized by two facets: the physical twin and its corresponding digital counterpart, illustrated in Fig. 4. Physical entities, augmented with smart devices, actively update sensing data to the cyber space (P2C). In turn, the cyber space provides control signals to adjust and optimize the behaviors of real-life objects (C2P). The physical twin is defined by five key attributes: geometry, structure, property, behavior, and rule. Geometry encompasses visualization attributes, such as positions, sizes, and shapes. Property represents internal physical attributes like function/capacity, stress, resistance, and temperature. Structure denotes spatial and functional relationships among sub-components of an object. Behavior encapsulates the dynamic capacities and output events of the entity. Rule is employed to articulate the domain knowledge of the object, including deductions, constraints, and associations (Tao and Zhang, 2017). The corresponding digital equivalent of the physical twin serves several functions. It facilitates real-time monitoring of resource states and project progress through perceptual data and cyber-physical interoperation (Opoku et al., 2021). Additionally, it enables virtual modeling, running simulations, and verification. During the implementation phase, a digital twin provides operational guidance and alerts for managers and workers. Advanced digital twin systems can also forecast future states and emergency events using predictive algorithms.

Quantitative analysis of digital twin research across multiple disciplines reveals a notable outbreak and rapid growth beginning in 2017, as illustrated in Fig. 5. The concept of digital twin has garnered substantial attention within academic circles, leading to extensive exploration across various research domains. Notably, the fields of engineering and computer science collectively contribute to over 50% of digital twin applications, underscoring its pivotal role in information integration and its direct impact on computer-aided industries. Within the realm of traditional industrial topics, digital twin adoption has experienced swift expansion in the construction sector, mirroring the overarching growth trajectory of the concept. Noteworthy areas of research within digital twin-enabled construction include construction machinery, safety, and

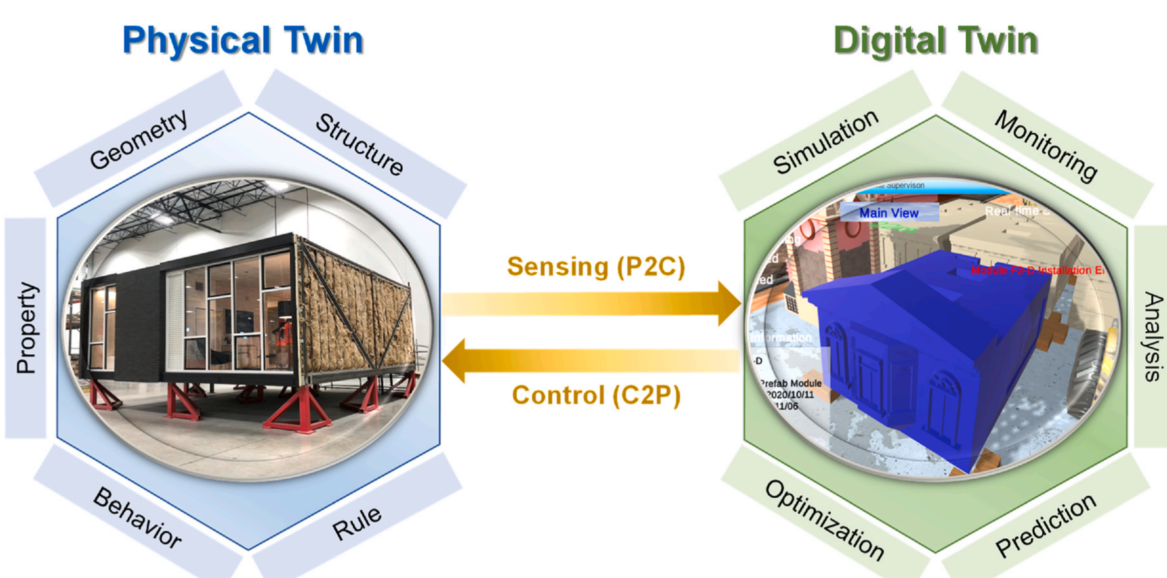

Fig. 4. Digital twin composition based on real-time interoperation.

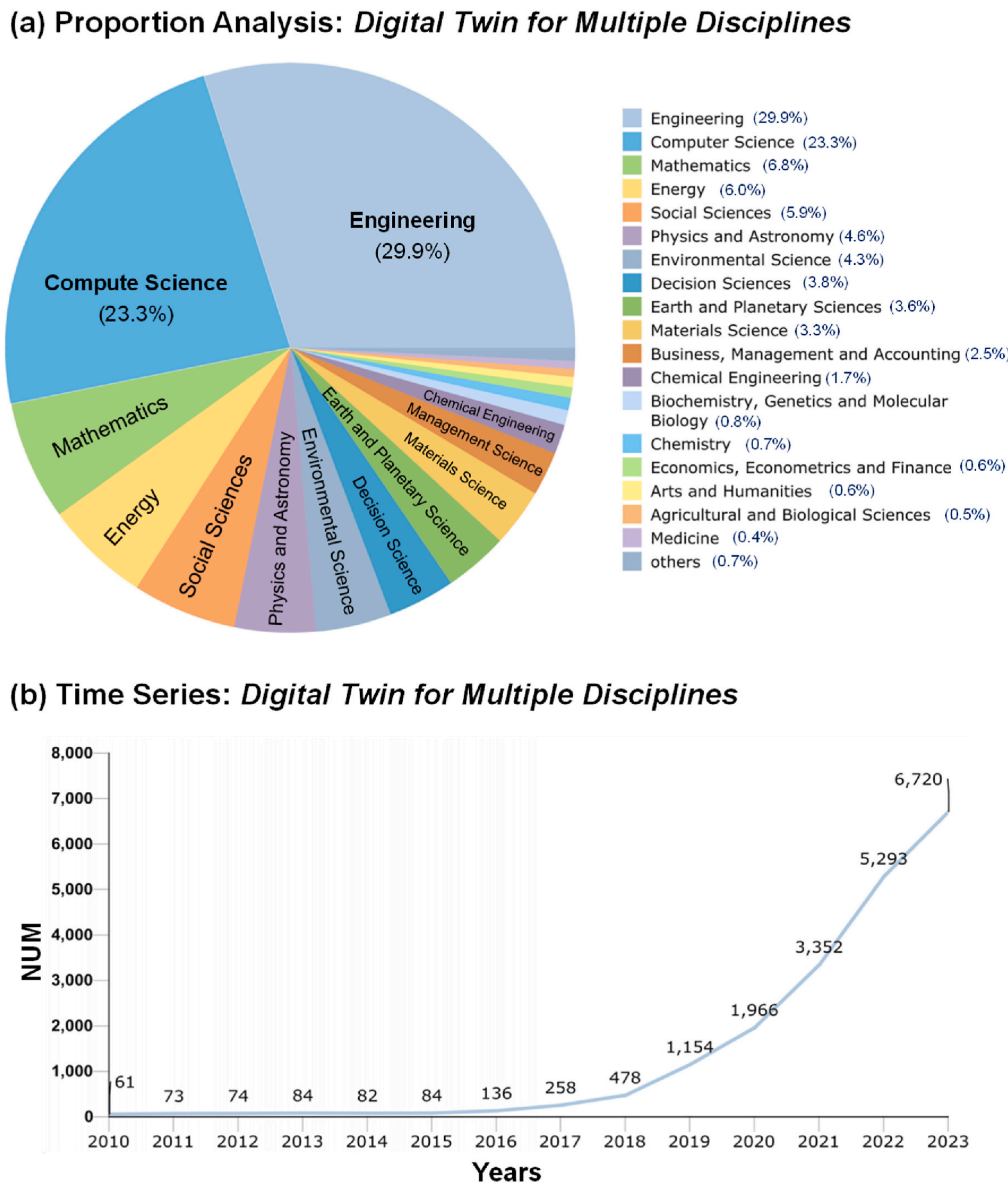

Fig. 5. Quantitative analysis of digital twin research for multiple disciplines. (a) Proportion analysis. (b) Time series.

quality, which emerge as the top three focal points, as shown in Fig. 6. The proliferation of digital twin applications in manufacturing underscores the burgeoning interest in leveraging this technology within construction machinery contexts. Moreover, addressing construction safety and quality stands out as imperative research priorities within the construction domain, with digital twin methodologies offering promising avenues for enhancing performance across these critical indicators.

For the generation of digital twins, various methods for generating digital twins from different perspectives have been investigated and compared in Table 2. The five-dimensional model is the most commonly adopted model of a digital twin, consisting of five key components—-physical entity, corresponding digital replica, service, fusion data, and connection (Tao and Zhang, 2017): (a) Physical entity: objects with specific functions; (b) Virtual model: digital equivalents of physical entities; (c) Service: functions such as management, control, and optimization provided for stakeholders; (d) Fusion data: core driver of the digital twin; (e) Connection: real-time integration and interoperation among physical entity, virtual model, and service through fusion data. On the basis of this model, Construction Digital Twin (CDT) is proposed as a socio-technical, process-oriented mapping of building components that enable collaborative management and operation (Boje et al., 2020). Another related concept, Digital Twin Construction (DTC), is introduced as a tool that utilizes real-time monitoring data and AI to optimize the construction lifecycle (Sacks et al., 2020). DTC integrates data clustering and the Plan-Do-Check-Act (PDCA) cycle to create a lean and closed-loop planning and control system. While CDT focuses on aiding construction execution and management, DTC presents a holistic model of construction management. Five conceptual layers are concluded for

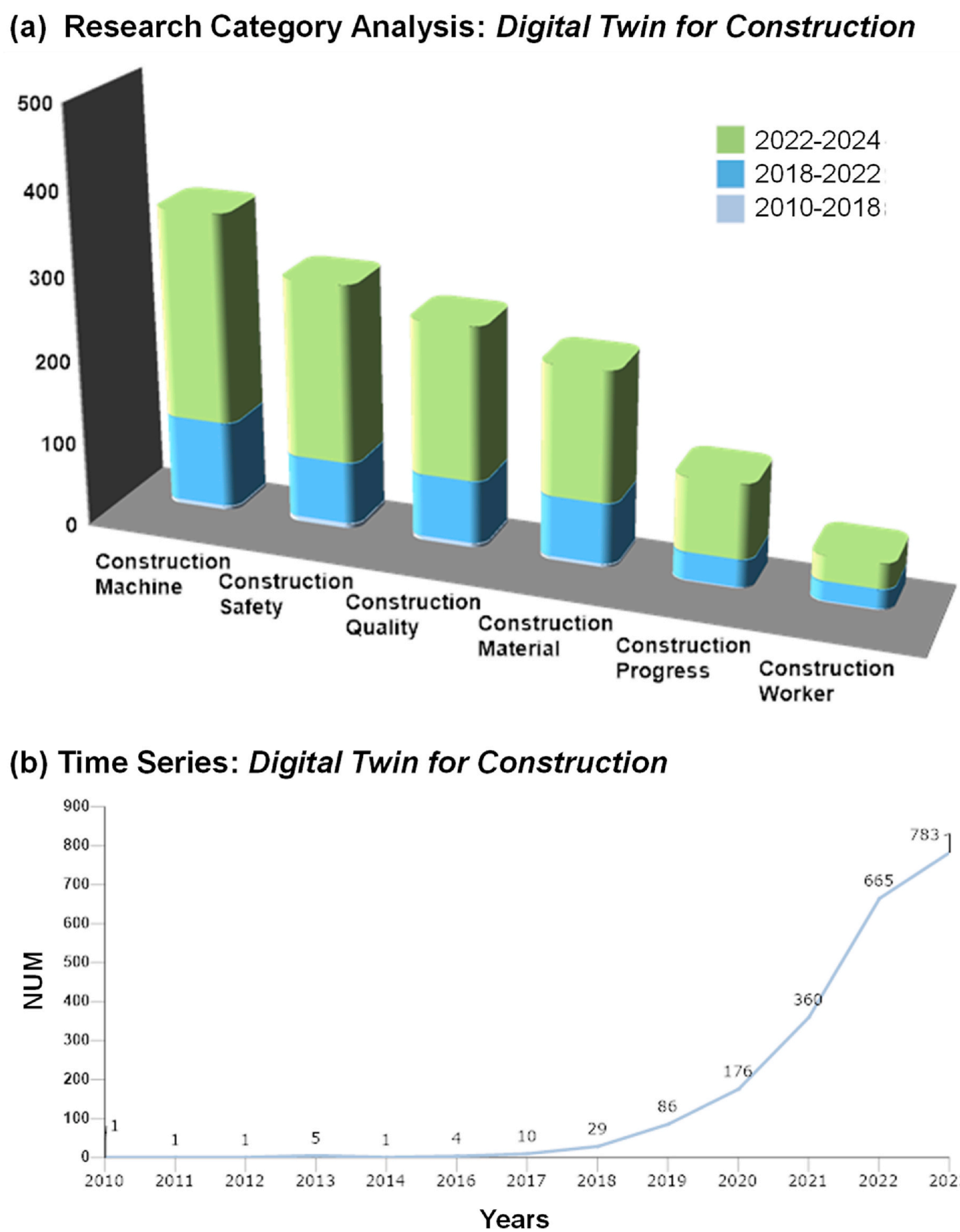

Fig. 6. Quantitative analysis of digital twin research for construction. (a) Category analysis. (b) Time series.

construction digital twins, including data acquisition, data transmission, digital modelling, data/model integration, and services. Based on this research, various technologies, methods, and platforms are applied for data collection, fusion and visualization (Tuhaise et al., 2023). According to Social Network Analysis (SNA), some hot areas which are significantly facilitated by digital twins are identified. For instance, real-time data is widely combined with construction digital twins, while researchers paid much attention to how real-time data can be used to monitor various assets, which regarding real time as a key characteristic of digital twin (Su et al., 2023). Decision making also occurs in the top five of most centrality measures, showing that decision making is a significant topic in the digital twin-based construction management (Arisekola and Madson, 2023). Moreover, many newly proposed information technologies are widely used to integrate with construction digital twins, and blockchain is the most popular one in recent years. Due to the unique advantages of blockchain, such as transparency, traceability, and high security, digital twins supported by blockchain could be applied for planning and design collaboration, document management, quality management, construction safety information management, tracking operation and maintenance costs, and

Table 2
Comparative chart of digital twin models.

DT Model	Key Elements	Main Functions	Characteristics
5 Dimension-DT (Tao and Zhang, 2017)	Physical entity, virtual model, service, data, and connection	Real-time monitoring and dynamic control	Interoperability and convergence
Cloud-based Cyber-Physical System (C2PS) (Alam and El Saddik, 2017)	Physical entity, virtual model, and connection	Computation, control, and communication	Stationary, mobility, and data center
Building Digital Twinning (BDT) (Yoon, 2023)	DT elements, functional requirements, and enabling techniques	Constructing, extending, verifying, and calibrating data, information, and models (DIM)	Comprehensiveness, omniscience, and flexibility
Digital Twin as a Service (DTaaS) (Aheleroff et al., 2021)	Physical layer, digital layer, cyber layer, and APP layer	Scheduling, real-time monitoring, remote control, and prediction	Effect, interaction, visibility, and service description
Biomimicry DT (S. Liu et al., 2021)	Geometry model, behavior model, and process model	Real-time observation, understanding and control	Multi-scale and multi-dimension
Ubiquitous Digital Twin Model (Jiang et al., 2023)	Six domains (*G*, *S*, *D*, *I*, *A*, and *T*)	Unified and structured description for digital twins	Generality and scalability
Resilient Digital Twin Model (Song et al., 2023)	Geometry asset, Mechanism asset, IoT data asset, Algorithm asset	High adoptability of digital twins to dynamic and uncertain scenarios	Resilience and generality

coordination of facility management services (Adu-Amankwa et al., 2023; Jiang et al., 2023; Li et al., 2021; Zhao et al., 2023). Current studies also prove that digital twins derive an advanced compatibility for different technologies, which could be further developed as an integration environment.

A remarkable discussion topic is the comparison between newly proposed construction digital twins and the original digital twins proposed in manufacturing industry. While construction digital twins draw inspiration from manufacturing models like the five-dimension model, there are notable differences that warrant exploration. This comparison can be approached from six key perspectives, including the working environment, operation scale, project timespan, granularity, stability, and capacity size, as shown in Table 3. In the construction sector, the built environment introduces challenges such as instability, large operational scales, high uncertainty levels, and non-standard specifications. These factors pose significant hurdles for achieving cyber-physical interoperability in construction digital twins. The prevalence of a higher number of random events further necessitates a broader compatibility range to accommodate diverse event types and state changes. The operational space in construction, given the larger and more complex nature of buildings, requires construction digital twins to operate at larger scales. This places heightened demands on system and hardware performance. Additionally, the extended timelines of construction projects, spanning months to even years, contribute to a longer temporal scale for construction digital twins. Furthermore, the granularity of construction digital twins, in comparison to manufacturing, is relatively more relaxed. This is attributed to the larger scale of building prefabricated elements, implying a greater granularity for construction digital twins. Overcoming the challenges related to the deployment of digital twin sensors and hardware within buildings is also crucial, considering that construction sites are less stable and less conducive to IoT deployment compared to controlled factory settings.

3.3. Analysis of construction management in construction 4.0

The overlay visualization of keywords about Construction Management with time scope from *2010/01/01* to *2023/05/31* is shown in Fig. 7. This timespan matches with the period of Construction 4.0 era. Broadly classified, there are several classic management problems, including supply chain management, risk management, safety management, and cost management.

The purpose of construction supply chain management is to enhance communication and collaboration among stakeholders, ensuring the seamless flow of goods, services, and funds within the construction supply chain (Dainty et al., 2001). In comparison to other industries, the supply chain management in the construction is subject to multiple challenges due to unique nature of one-time projects, large scale, extensive involvement of stakeholders, and long project cycles (AlMaian et al., 2015). In addition, the lack of trust among stakeholders, the fragmentation and discontinuity of the construction supply chain also cause great difficulties (W. S. Lu et al., 2021). This is closely related to the low efficiency and unsmooth communication among stakeholders, as well as the limited degree of digitalization within the industry (Zhai et al., 2019). To address this issue, numerous ongoing studies focus on leveraging of synergies between BIM and IoT to develop digital methods and systems for construction supply chain management while ensuring the data security (Niu et al., 2017; Xue et al., 2018).

Currently, there are still many problems and opportunities for the further study, such as the accuracy (W. S. Lu et al., 2021), diversity (Deng et al., 2019) and safety (Qian and Papadonikolaki, 2021) of the data collection and sharing, collaborative planning and design methods

Table 3
Comparisons between construction digital twins and manufacturing digital twins.

Dimensions	Construction Digital Twins	Manufacturing Digital Twins
Working Environment	Digital twins work for outdoor condition of construction sites, which is combined with a plane ground with a 3D building working space.	Digital twins work for indoor conditions of factories, which is always a standard and stable working environment.
Operation Scale	Comparatively larger scale; Horizontal dimension (Rooms) and vertical operation dimension (Floors);	Comparative smaller scale; Mainly horizontal dimension.
Project Timespan	Comparatively longer period (mainly 1 year −5 years)	Comparatively shorter period (mainly 1 month - 1 year)
Granularity	Larger objects (e.g., prefabricated component, concrete, steels, and trucks)	Smaller objects (e.g., machine elements or materials)
Stability	Unstable. (1) Working process is easily influenced by many unexpected disturbances, such as rain or dust. (2) Operation (e.g., components lifting, components installing) are difficult to standardize and control.	Comparatively stable. (1) Working process is conducted in indoor condition with low uncertainty effected, which is resistant for disturbances. (2) Operation (e.g., material production, processing, material assembly) are standardized and more effective to control.
Capacity Size	Construction project contains more events and states caused by the highly spatial-temporal scale and high operational complexity and uncertainty, requiring a larger capacity size for digital twins.	Manufacturing has comparatively fewer events and states based on more stable and standardized operation procedure, requiring a larger capacity size for digital twins.

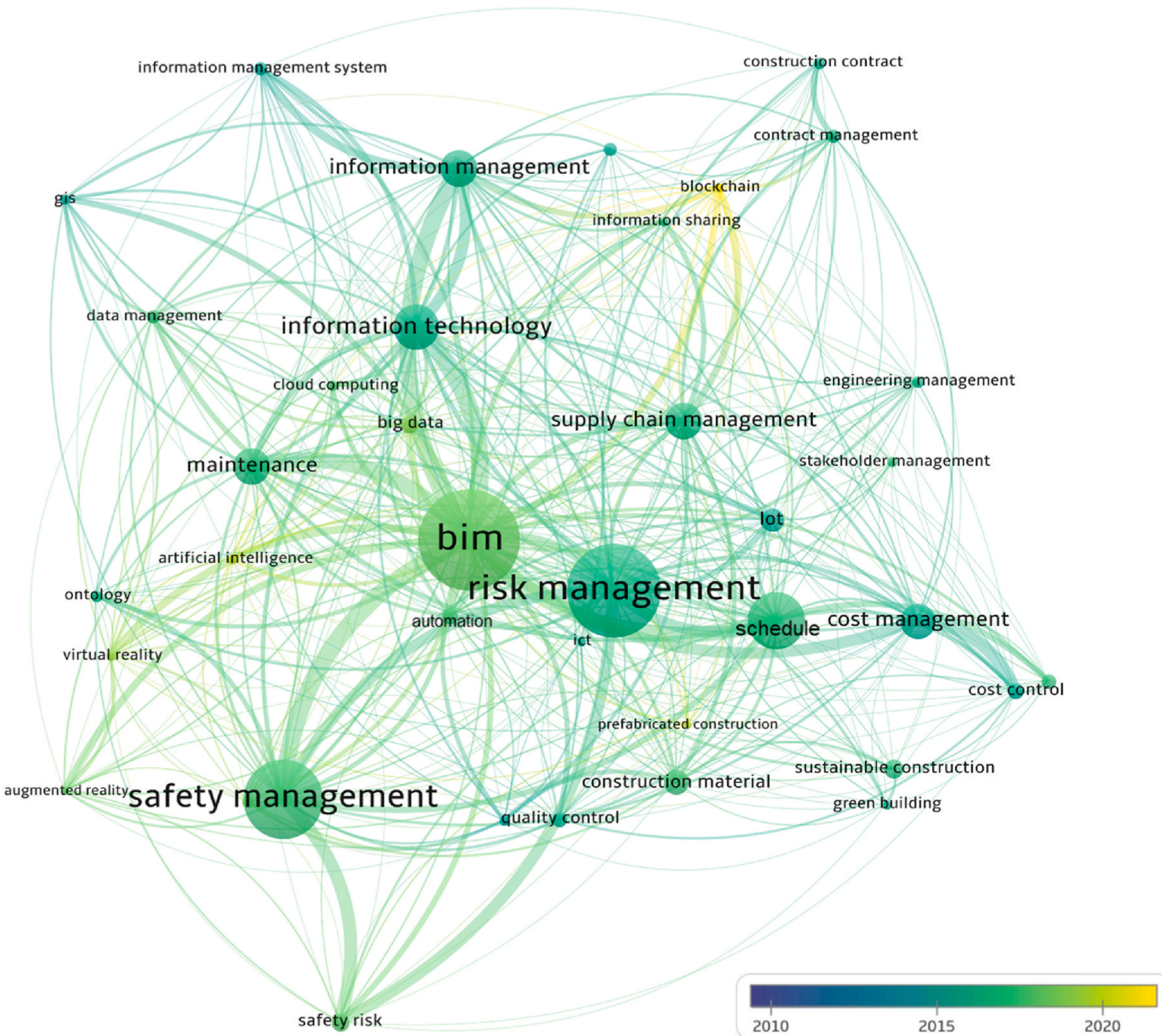

Fig. 7. Overlay visualization of research keywords about Construction Management with timeline (Input: **Construction Management**, Scope: from 2010/01/01 to 2023/05/31).

(Le et al., 2020), and intelligent decision-making methods (Yildiz and Ahi, 2022). On the other hand, risk management in construction encompasses a broad range of activities, including risk identification, influence risk decision-making, risk monitoring, analysis of risk responses, among others (Edwards and Bowen, 1998). Indeed, risk management plays a crucial role throughout various stages of a construction lifecycle, including design (Y. Lu et al., 2021), pre-construction (M. Li et al., 2018), construction (Kwon et al., 2018), maintenance (Wang et al., 2021), and the final demolition (Akhtari et al., 2021). Among them, the risk-related issue in the construction process attracts the greatest attention from researchers. But in the future, there will be a growing emphasis on proactively eliminating construction safety hazards through safety and scientific design (Hossain et al., 2018). Studies have demonstrated that approximately 50%–60% of construction accidents could be prevented through work in the design stage (Gambatese et al., 2008). Currently, the safety-oriented design methods have not received widespread attention. Construction maintenance is also a widely studied topic combined with construction digitalization, including cities, infrastructures, bridges, transportation systems, and safety management, which is tailored to construction sustainability (Ding et al., 2023; Zhang et al., 2023). Technological concepts like digital twin are applied for the environmental assessment and protection to achieve a more sustainable construction industry (Boje et al., 2023; Su et al., 2023).

From the perspective of computational optimization in practical project management, the problems can be predominantly segregated into two categories: resource-constrained project scheduling problem (RCPSP) and resource-leveling problem (RLP) (Senouci et al., 2001; Taghaddos et al., 2021). RCPSP, a prominent NP-hard optimization problem in construction management (Liu et al., 2017), involves scheduling activities while considering resource constraints and precedence relationships to optimize objectives, such as makespan, holding time, tardiness, and cost. RLP always exists in repetitive construction projects scheduling activities deliberately so that each crew may work continuously from unit to unit without interruptions (Su and Lucko, 2016). Stakeholders aim to reduce resource fluctuations over time, and resource leveling algorithms focus on smoothing resource histograms and reducing peak resource demand. Except the well-known studying problems mentioned above, there are other specific problems in construction industry, such as on-site crane management. Crane operation optimization focuses on the following aspects: (i) optimizing the number of tower cranes, types of cranes, and their setup locations within the available site area; (ii) simulating the operating paths of tower cranes to prevent overlapping and collision accidents, and (iii) optimizing work schedules and sequences to minimize the movement distances and travel times of tower cranes' hooks (Huang and Wong, 2018). For another perspective, scheduling is also a critical aspect of project management that can significantly impact efficiency and cost, which can be classified into online scheduling and offline scheduling. Online scheduling refers to the real-time adjustment and optimization of tasks and resources based on the latest project data and constraints (Jiang et al., 2024). This approach leverages digital technologies (e.g., IoT, machine learning, and AI) to continuously monitor and update project plans and schedules, ensuring that tasks are completed on time and within budget. Online scheduling enables agile and adaptive project management, allowing teams to quickly respond to changes and optimize project outcomes (Li and Wang, 2020). Offline scheduling, on the other hand, involves the creation of a static project plan in advance of the project's start date, typically using traditional project management tools such as Gantt charts.

Drawing from a comprehensive review of prior studies on Construction 4.0 and construction management, it is evident that while digitization and automation offer substantial advantages, certain critical aspects have not received adequate attention, leading to an incomplete and less holistic understanding of Construction 4.0. This research emphasizes three pivotal motivations that serve as foundational principles for proposing a novel management paradigm in future construction:

Motivation 1: *Recognizing the paramount importance of the human element in society, prioritizing safety and health considerations in construction projects is imperative.*

Motivation 2: *Acknowledging that in the absence of uncertainty, where everything adheres to predefined plans, the application of digitalization technologies for real-time monitoring and control may be deemed unnecessary due to deterministic outcomes.*

Motivation 3: *Emphasizing the significance of environmental concerns, particularly in light of the considerable pollution generated by traditional construction practices in previous decades.*

In addressing these motivations for future construction management, there arises a compelling need for a new roadmap that encapsulates the entirety of Construction 4.0's principles and technologies, providing a more comprehensive and detailed understanding of the evolving landscape.

4. Roadmap from construction 4.0 towards future management mode

According to the analytics and motivations concluded in Section 3, the roadmap from Construction 4.0 towards the outlook is proposed. The roadmap consists of two key components: a roadmap framework comprising six steps and an orthogonally synchronized digital twin model for the future of construction. Building upon the earlier analysis and stated motivations, three fundamental elements are put forth: human centricity, sustainability, and resilience.

4.1. Roadmap framework for future construction

To fulfill the three motivations mentioned in the previous section, future construction concentrates on a more human-centric, resilient, and sustainable construction industry through information and automation technologies, achieve more efficient design and operation, save more resources to reduce environmental and social impact, as well as improve the productivity and competitiveness of the entire industry (Marinelli, 2023). As depicted by the development framework in Fig. 8, the future of construction prominently emphasizes three key developmental components rooted in Construction 4.0: Human-centricity (**M1**), Resilience (**M2**), and Sustainability (**M3**). These components are expounded as follows.

(1) **Human-centricity** (for **M1**): Human-centricity entails the design and construction of infrastructures prioritizing human emotional well-being, safety, security, worker productivity, and a conducive environment. This involves creating spaces that enhance human mental and physical health, incorporating elements such as natural light, greenery, and areas for relaxation and exercise. Future construction places a significant emphasis on worker safety and security, encompassing aspects like fire safety, disaster resilience,

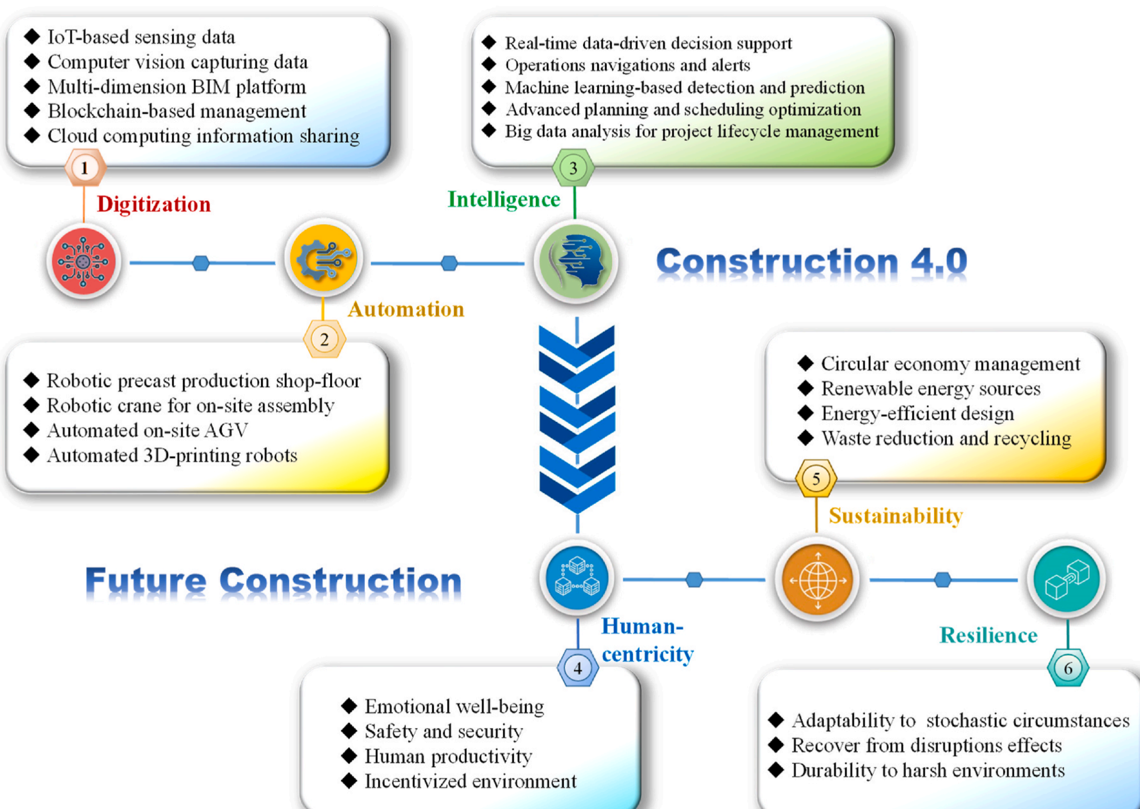

Fig. 8. Roadmap framework from Construction 4.0 towards future construction.

and cybersecurity measures. Establishing an incentivized environment involves designing spaces that foster collaboration, creativity, and innovation, along with providing amenities such as ergonomic workstations and flexible working arrangements.

(2) **Resilience** (for **M2**): Resilience extends beyond the physical capacity of infrastructures to withstand natural disasters or disruptions; it encompasses the adaptability of construction management to navigate uncertainties and dynamically changing circumstances. Achieving resilience in future construction involves integrating advanced digital technologies into the construction management process. This includes leveraging real-time data analytics, cloud computing, and mobile technologies to enhance risk management, detect/predict hazards, and dynamically replan/reschedule.

(3) **Sustainability** (for **M3**): Sustainability serves as a foundational principle guiding the design, construction, operation, and maintenance of buildings. This encompasses the use of green materials (e.g., green roofs, renewable energy sources, and recycled or locally sourced materials), sustainable operations minimizing waste and reducing energy consumption (e.g., energy-efficient, and resource-conserving systems), and adherence to circular economy principles (e.g., recycling construction and demolition waste). The goal of sustainability is to mitigate environmental impacts and enhance the long-term livability of the built environment.

For the attributes analysis of the proposed roadmap, the key dimensions are divided into the cyber domain, which is technology-oriented, and the engineering domain, which is principle-oriented, as shown in Fig. 9. Within the cyber domain, the focus is primarily on the technological environment based on information and automation technologies. Automation is a critical dimension, structured into three levels of sophistication. Initially, automation involves providing navigations and alerts to users, progressing towards human-robot collaboration (HRC), and ultimately aiming for full automation throughout the construction lifecycle. Digitization plays a crucial role, evolving from basic sensing and simple data updating to real-time analysis capabilities, which can offer more valuable processed information. At a high level of digitalization, predictive functions are integrated to provide stakeholders with advanced information ahead of time, enhancing decision-making processes. Intelligence is another key attribute for future construction management, encompassing various levels of sophistication. Intelligence at the execution level focuses on short-term tasks and immediate problem-solving. Intelligence in planning addresses mid-term objectives, optimizing resource allocation and scheduling. Finally, intelligence at the strategic level takes a long-term perspective, guiding overarching decisions and adapting to changing market dynamics.

Within the engineering domain, three principle-level dimensions are involved following the roadmap structure.

- **Human-centrality dimension**: There are four levels in human-centrality dimension, including feeling, privacy, productivity, and safety. Feeling focuses on creating environments that promote positive emotional experiences for individuals involved in or impacted by the construction project. It involves considerations such as aesthetics, comfort, and psychological well-being. Privacy is a critical aspect of human-centric design, particularly in construction projects that involve residential or sensitive spaces. This level addresses measures to ensure individuals' privacy is respected and maintained throughout the project lifecycle. Productivity is essential for optimizing resource utilization and achieving project goals efficiently. This level involves implementing strategies and technologies to streamline workflows, reduce downtime, and improve overall productivity across various project phases. Safety is paramount in construction, and this level focuses on implementing measures to protect the health and well-being of workers, residents, and the surrounding community. It includes aspects such as hazard identification, risk mitigation, and adherence to safety regulations.
- **Sustainability dimension**: There are four levels in sustainability dimension, including material, energy, ecology, and society. Material level emphasizes the selection and use of sustainable materials that minimize resource depletion, reduce waste generation, and promote recyclability or biodegradability. It involves considerations such as material sourcing, life cycle assessment, and embodied carbon footprint. Energy efficiency is crucial for reducing greenhouse gas emissions and mitigating climate change impacts. This level addresses strategies for optimizing energy consumption throughout the construction lifecycle, including building design, energy-efficient systems, and renewable energy integration. Ecological considerations encompass preserving biodiversity, minimizing habitat disruption, and promoting ecosystem resilience. This level involves implementing green infrastructure, habitat restoration measures, and biodiversity conservation strategies to mitigate construction-related ecological impacts. Sustainability extends beyond environmental concerns to encompass social equity and community well-being. This level focuses on fostering inclusive development practices, promoting social responsibility, and addressing the needs of diverse stakeholders, including marginalized communities.
- **Resilience dimension**: There are three levels in resilience dimension, including building structure, management, and community.

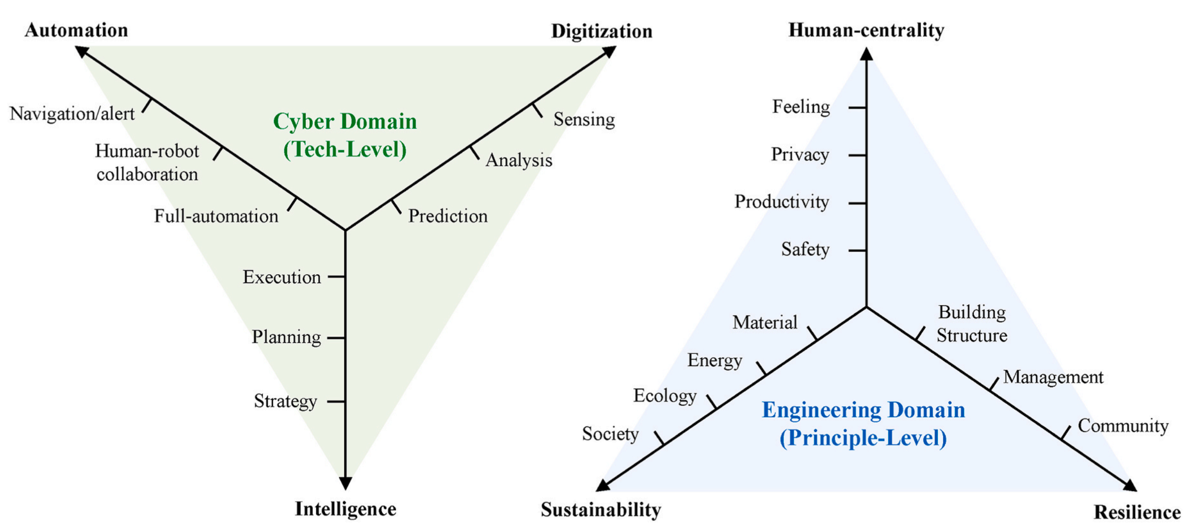

Fig. 9. Dimensional analysis of attributes of the proposed roadmap.

Building structure emphasizes designing and constructing buildings and infrastructure to withstand natural hazards such as earthquakes, hurricanes, and floods. It involves incorporating resilient design principles, adopting resilient materials, and ensuring structural integrity to enhance building resilience. Effective management practices are essential for ensuring the resilience of construction projects and minimizing disruptions during and after adverse events. This level involves developing comprehensive risk management plans, implementing emergency response protocols, and integrating resilience considerations into project management frameworks. Resilience at the community level involves building social cohesion, fostering community engagement, and enhancing adaptive capacity to respond to and recover from disasters. This level focuses on promoting community resilience through education, capacity-building initiatives, and collaborative partnerships with local stakeholders.

In summary, the future of construction revolves around three core principles: Human-centricity, Resilience, and Sustainability, within the framework of Construction 4.0. Human-centricity focuses on designing infrastructure prioritizing emotional well-being, safety, and productivity, creating spaces that promote health and incentivized environments. Resilience extends beyond physical infrastructure to encompass construction management, leveraging digital technologies for risk management and dynamic adaptation. Sustainability guides the entire lifecycle, emphasizing the use of green materials, sustainable operations, and circular economy principles to minimize environmental impact and enhance long-term livability.

4.2. Synchronized digital twin (SDT) model for future construction management

The core mechanism for future construction management is orthogonal synchronization among humans, machines, materials, operations, and energy. Real-time cyber-physical integration and interoperation among the resources is coordinated by digital twin systems, which is an integrated environment of various technologies. Hence, an orthogonally Synchronized Digital Twin (SDT) model is formulated containing both horizontal synchronization (H-Sync) and vertical synchronization (V-Sync) to illustrate the core mechanism of construction management, as shown in Fig. 10. The mathematical model of SDT is designed to further reveal and explore the orthogonally synchronized digital twin concept. Through formulas (1)-(8), the key elements, functional mechanism, and constraints of digital twins for construction management can be concretized and better understood for construction scholars and workers.

Orthogonal synchronization pertains to the coordination and maintenance of a specific relative relationship among multiple objects or activities within a constrained spatial-temporal domain. The purpose is to ensure the continuous connection and alignment of these objects or activities throughout their evolving processes (Jiang et al., 2022). Within the context of SDT, two essential synchronizations are distinguished: horizontal synchronization (H-Sync) and vertical synchronization (V-Sync). V-Sync entails real-time bidirectional synchronization between physical space and cyber space, facilitating the seamless connection and interoperability of physical resources and operations with their corresponding digital twins. On the other hand, H-Sync involves coordinated interactions among diverse construction resources, operations, human elements, and energy. The objective of H-Sync is to

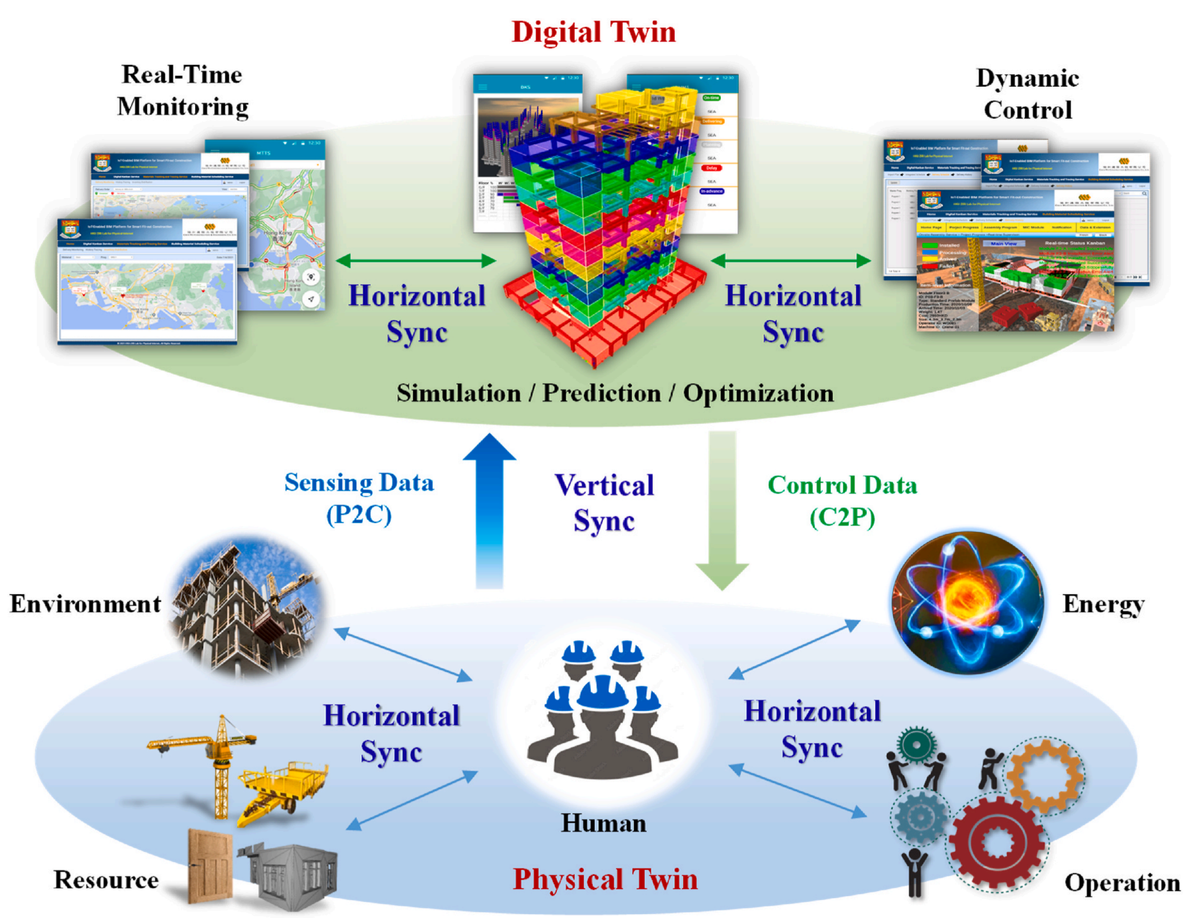

Fig. 10. Orthogonally Synchronized Digital Twin (SDT) model for construction management.

execute appropriate operations using suitable resources and energy at the right time and location, all while prioritizing human well-being.

The regular expression of SDT model is shown in Formula (1). S is the finite and nonempty set about the states of construction resources, such as in-delivery, site-arrival, installed, and warning; E is the set about events and operations in construction projects, which can transfer the resource state; $\langle W, K, M\rangle$ is the set of construction resources including workers, energy, and materials involved in the project; $\langle t_I, t_O\rangle$ is the timespan of state about input time stamp and output time stamp; λ is the transfer function for state transition triggered by an event, as shown in Formula (2). The spatial-temporal trajectory model $Tra(M_i)$ for resources is applied for real-time state tracing. The historical states of key materials and machines containing required energy and workers at specific time stamp can be traced using digital twins, as shown in Formula (3).

$$DT_F = \{S, E, \langle W, K, M\rangle, \langle t_I, t_O\rangle, \lambda\} \tag{1}$$

$$\lambda : S \times E \rightarrow S \tag{2}$$

$$Tra(M_i) = S_1 \overset{\langle E_1, W_1, K_1, t_I^1, t_O^2\rangle}{\Rightarrow} \dots \overset{\langle E_{j-1}, W_w, K_k, t_I^{j-1}, t_O^j\rangle}{\Rightarrow} S_j \overset{\langle E_j, W_w, K_k, t_I^j, t_O^{j+1}\rangle}{\Rightarrow} \dots \overset{\langle E_n, W_w, K_k, t_I^{n-1}, t_O^n\rangle}{\Rightarrow} S_n \tag{3}$$

V-Sync represents a bidirectional interoperation process occurring in real-time between physical space and cyber space. This process encompasses two directional data flows: real-time sensing (P2C), where data flows from the physical to the cyber domain, and dynamic control (C2P), where data flows from the cyber to the physical domain. Real-time sensing involves the transfer of up-to-the-minute data regarding construction resource information (e.g., status, location, and environmental details) to digital twins through IoT-based infrastructures. BIM model is updated at predefined intervals, reflecting the current construction progress for stakeholders. The dynamic control process is to send the decision supports to operators for dynamic adjustment. Real-time navigations and alarms are also provided to support the daily tasks to improve the operation efficiency and accuracy. Two data flows are intertwined together to form V-Sync. To achieve the near-real-time synchronization between physical space and cyber space, the time delay of bidirectional interaction of P2C and C2P are limited. For P2C flow, digital twin updating is controlled within a predefined range d_V, as shown in Formula (4). Thus, the current state about the construction resource and project progress can be reflected to stakeholders in a timely manner. While for C2P flow, the decisions should be made based on real-time project situation and then provides feedback for operators in a timely manner. Except the systematic delay range d_V^{C2P}, the delay of decision-making duration t_{DM} is also considered for the temporal limitation of C2P flow, as shown in Formula (5).

$$t_C(S_i) - t_P(S_i) \le d_V^{P2C} \tag{4}$$

$$t_P(S_i) - t_C(S_i) \le d_V^{C2P} + t_{DM} \tag{5}$$

H-Sync is the coordination of events in the construction workflow to conduct operations to the right resources with minimized energy at suitable time and location in unison. H-Sync happens both in physical space and cyber space, which are mirrored through V-Sync. The transition time stamps of one state to another state should be maintained in a certain relationship. For some resources and operations, the time gap with subsequent ones should not be too short or either too long, which are respectively described in Formula (6) and (7) to represent the time gap limitation in physical space and cyber space, where d_H' is the lower limit, d_H'' is the upper limit, and $x_j^w(\bar{t})$ is the binary variable for the allocation of worker w to the operation j around time stamp $\bar{t}$. Formula (8) means that the consumable energy of operation j should be controlled below a threshold $EN(\bar{t})$ with an auxiliary variable $\omega(\bar{t})$.

$$d_H' \le |t_P(S_{i+1}) - t_P(S_i)| \bullet x_j^w(\bar{t}) \le d_H'' \tag{6}$$

$$d_H' \le |t_C(S_{i+1}) - t_C(S_i)| \bullet x_j^w(\bar{t}) \le d_H'' \tag{7}$$

$$k_j \bullet x_j^w(\bar{t}) \le EN(\bar{t}) + \omega(\bar{t}) \tag{8}$$

In SDT model, the intricate interplay between V-Sync and H-Sync mechanisms is crucial. V-Sync, as the bidirectional real-time synchronization process between the physical and cyber spaces, provides critical data support for H-Sync's coordinated operations in both domains. V-Sync's advanced technologies seamlessly gather up-to-date data on construction resources, environmental parameters, and pertinent information, which is subsequently transmitted through robust IoT infrastructures to update the digital twins in real-time, accurately reflecting the current resource states and construction progress. For instance, in the context of V-Sync domain, a technology such as real-time sensor fusion can support numerous applications in the H-Sync domain. Data from multiple sensors are combined to provide a comprehensive understanding of the physical environment, which is essential for H-Sync to coordinate resource allocation, operational execution, and energy management. Conversely, H-Sync's operational decisions and planning rely heavily on the real-time data fed by V-Sync. Through the dynamic control (C2P) process, H-Sync's strategic directives are promptly communicated back to the physical workspace, guiding on-site operations and ensuring optimal resource utilization and energy efficiency. This two-way data exchange forms a closed-loop feedback system, where the outcomes of H-Sync's decisions are monitored and analyzed by V-Sync, further refining and optimizing the decision-making models. The technical sophistication of the SDT model lies in the intricate network of data flows and interactions between V-Sync and H-Sync. Technologies such as IoT, BIM, and advanced analytics play pivotal roles in facilitating this exchange, ensuring the model's adaptability, responsiveness, and overall effectiveness. By harnessing these technologies, the SDT model advances the digital transformation of construction management, enabling more coordinated, efficient, and sustainable construction practices.

Overall, SDT model provides a unified and structured language for industrial stakeholders and researchers to generate and operate construction digital twins. It's easier for stakeholders to achieve a shared understanding of the overall systematic framework and specific functional modules. The reason why we need synchronization lies on the fact that future construction management contains too many technologies and business processes. The seamless collaboration is required and needs a strong systematic approach to connect each part together into a holistic system. The synchronization described by SDT focuses on the spatial-temporal regulation both for the physical entities and digital equivalents. This regulation also ensures a coordinated and aligned workflow among humans, machines, materials, operations, and energy.

As outlined in the roadmap and the synchronized digital twin model proposed, there exists a clear distinction in the application of current and future digital twins in construction. A comprehensive comparative analysis spanning core objects, operational environments, core interoperability, key data types, computational complexity, and services is presented in Table 4. This comparative overview serves to accentuate the advancements and subtle modifications that digital twins undergo during the transition from current construction practices to prospects.

5. Digital twin-enabled intelligent management in future construction

Under the context of future construction, the objectives for digital twin-based construction management, such as minimizing the required efforts or maximizing the desired benefits, can be more efficiently and consistently optimized in complex and uncertain conditions through novel theoretic and technological development (Chong and Zak, 2013; Tang et al., 2018).

Table 4
Comparisons between current digital twins and future digital twins in construction.

Dimensions	Current Digital Twins	Future Digital Twins
Core objects	Machines/Materials/ Structures	Humans/Environment
Operational environment	Stable/Deterministic	Complex/Stochastics
Core interoperability	Vertical cyber-physical synchronization	Horizontal multi-domain synchronization
Key data types	Real-time sensing data	Hybrid timespan data
Computational complexity	Normal spatial-temporal complexity	High complexity for multi-domain synchronized computation
Services	Progress monitoring/ Decision-making/ Information sharing	Full-range interdisciplinary supports

5.1. Information and automation technologies for digital twin construction

Information and automation technologies lay the groundwork for digital twin-based intelligent management in future construction era, which are also the foundation for the mechanism of H-Sync and V-Sync. The following sections delve into a handful of pivotal enabling technologies are analyzed as follows.

- *Internet-of-Things (IoT)*: IoT is the fundamental element for construction digital twins providing the P2C sensing bridge, forming the upward direction of V-Sync. Smart Construction Object (SCO) is developed based on IoT technologies, which is always on the bottom of system framework to support the up-layers consisting of digitalization functions and smart services for digital twin systems (Niu et al., 2016). SCOs are traditional construction resources like workers, machines, and materials, enhanced with autonomy, awareness, and communicativeness through the integration of IoT-enabled devices such as Radio Frequency Identification (RFID), Ultra-Wide Band (UWB), and Global Positioning System (GPS) devices (Niu et al., 2017). Under the seamlessly management, control, and coordination by smart gateway, SCOs provide the real-time visibility and traceability to reflect the real-time component status and construction progress for collaborative decision-making and operation (Zhong et al., 2017). Hence, IoT not only enhances the traditional H-Sync among various resources but also augments it with communication abilities, facilitating a more coordinated and intelligent management of construction projects. However, there are certain limitations associated with RFID-enabled operations, including manual detection, mixed data, and inflexible gateway deployment (Li et al., 2017). To address these limitations, proactive positioning technologies such as UWB and GPS are applied for construction material and progress tracking. Compared to RFID, these technologies offer automatic active 3D positioning and have demonstrated centimeter-level accuracy and near-real-time performance in construction scenarios (Maalek and Sadeghpour, 2013; Park et al., 2016; Yin et al., 2009).
- *Computer Vision (CV):* Computer vision techniques also have been widely studied for real-time monitoring, safety assurance, and productivity analysis on construction sites, which is also a widely applied technology to generate digital twins (Fang et al., 2020; Paneru and Jeelani, 2021). The object detection methods can be utilized to identify whether workers appropriately wear personal protective equipment (Delhi et al., 2020), as well as identify categories, location and numbers of on-site objects (Jeelani et al., 2021; Zhao et al., 2024). The key points detection methods are employed to detect joints of workers and further recognize unsafe behaviors of workers (Xiang et al., 2023). The motion status of construction machines (e.g., excavators) can also obtained be by analyzing their joints (Assadzadeh et al., 2022). Besides, the semantic information extraction methods also have been studied to describe the conditions of construction sites (H. Wu et al., 2021). Furthermore, the productivity analysis methods also have been designed to analyze the working time, idle time and cycle time of on-site construction machines, so as to save cost and ensure the timely competition of construction project (Chen et al., 2023). Real-time monitoring of workers and machines' movements captured by CV systems provides critical data to update digital twins, reflecting the P2C bridge in V-Sync. The dynamic image information enables coordinated resource allocation and operation optimization, reflecting H-Sync's ability to coordinate diverse resources and operations.
- *Industrial wearables:* In Construction 4.0, industrial wearable technology plays a significant role in safety monitoring and management on construction sites, serving as a hardware support for construction digital twins. Wearable devices can be embedded in construction workers' helmets, gloves, and shoes, utilizing sensors to monitor their physiological status and environmental parameters in real-time manner (Li et al., 2019). For instance, wearable devices can track workers' heart rate, body temperature, respiratory rate, as well as the temperature, humidity, and gas concentration of the working environment (Kong et al., 2018). By conducting real-time monitoring and data analysis, potential safety risks such as fatigue, overexertion, and environmental hazards can be promptly identified, enabling appropriate measures to be taken to enhance work safety and health (Svertoka et al., 2021). Furthermore, industrial wearable technology can be employed for positioning and navigation purposes on construction sites. By integrating technologies like Global Positioning System (GPS) and Inertial Measurement Unit (IMU), wearable devices can track workers' location and movement trajectories in real-time. This proves to be beneficial for personnel management, task allocation, and progress control on construction sites. Additionally, wearable devices can provide real-time access to construction blueprints and instructional information, assisting workers in their construction operations and enhancing accuracy and efficiency. The data updated by industrial wearables informs human-centric decisions for task allocation and scheduling, aligning with H-Sync for executing operations with minimized impact on human well-being. Wearable devices transmit real-time data to digital twins, enabling dynamic control measures like alerts and instructions to be sent back to workers. This closed-loop feedback system epitomizes V-Sync's bidirectional synchronization process.
- *Big data*: Data is the key driver both for the real-time analytics and decision making under digital twin environment. During construction management, massive heterogeneous data from procurement, controlling, contracting, BIM, bidding, tendering, and site information continuously generate (Lu et al., 2015; Yilmaz et al., 2023). Big data is the analysis of large data sets to identify patterns and derive insights for business process (Ngo et al., 2020), which changes the operational dynamics of businesses and improves the productivity, decision making, and organizational capabilities (Ram et al., 2019). Big data has three key characteristics, namely "5V", which includes volume, variety, velocity, veracity, and value. *Volume* refers to the quantity and scale of data, which are growing explosively and extends beyond our capacity of handling large data sets; *Velocity* refers to the fast generation and transmission of data by efficient collection and processing from social networks and internet infrastructures; *Variety* refers to the diverse data forms and in which model and structural data are archived; *Veracity* refers to the diversity of quality, accuracy, and trustworthiness of the data (Yang et al., 2016). Big data can capture throughout the construction project lifecycle for improved decision making and enhance the effectiveness of project management (Yu et al., 2020). For H-Sync's cross-domain coordination capabilities, big data analysis of procurement, controlling, and other construction processes reveals patterns and insights that inform coordinated resource management and operation

optimization. The volume, variety, and velocity of big data enable near real-time updates of digital twins, facilitating V-Sync's seamless connection between physical and cyber spaces. In smart construction environment, the dynamic nature of real-time data collected by sensors follows the streaming of data sources (Bilal et al., 2016). Utilization of these real-time data to determine and adjust construction process to achieve human-centric H-Sync is the next frontier in future construction management.

- *Artificial Intelligence (AI)*: In the context of Construction 4.0, AI technology plays a critical role in enabling the construction management mode to innovate and transform in digital twin systems. AI refers to computer systems that are designed to perform tasks that would normally require human intelligence, such as learning, problem-solving, and decision-making. In the construction industry, AI is being used to automate tasks, analyze data, and optimize performance, among other applications (Pan and Zhang, 2021b). The technical aspect of AI technology is a key feature that sets it apart from other digital technologies used in the construction industry (Abdirad and Mathur, 2021). AI systems use machine learning algorithms such as neural networks, decision trees, and support vector machines to process large amounts of data and learn from that data, making them capable of adapting to new situations and improving their performance over time (M. Pan et al., 2022). This enables AI to be used for a wide range of applications, from predictive maintenance to safety monitoring, and even autonomous construction equipment. Moreover, AI technology is constantly evolving and improving, driven by advancements in machine learning algorithms such as deep learning, reinforcement learning, and natural language processing, as well as improvements in computer processing power and data collection and analysis. AI-driven predictive maintenance and optimization models coordinate maintenance schedules and resource allocations, ensuring operations are executed with minimal disruptions and costs, supporting H-Sync for coordinated execution. For V-Sync's bidirectional synchronization, AI algorithms analyze real-time data from sensors and other sources to update digital twins. Coordinated decisions are then sent back to the physical space through dynamic control mechanisms.
- *Robotics*: Robotics technology is playing an increasingly important role for the dynamic control in digital twin construction systems. Robotics is being used to automate a wide range of tasks, such as logistics, bricklaying, welding, and painting (Davtalab et al., 2018). Construction robots rely on advanced sensors, control systems, and algorithms to navigate construction sites and perform their tasks with precision and efficiency (Cai et al., 2019; Lee et al., 2021). By automating these tasks, robotics technology can significantly improve operation efficiency and accuracy, while also reducing the need for human labor (Davtalab et al., 2018). It has the potential to not only reduce costs but also improve human safety and security. Construction sites are inherently dangerous, and the use of robots can help to minimize the risk of accidents and injuries. Robots can be used to perform tasks in hazardous or hard-to-reach areas, allowing human workers to remain safely on the ground. There are a wide range of different types of robots that can be used in construction, from large-scale autonomous machines to small and specialized robots designed for specific tasks. Industrial robots, such as robotic arms and automated guided vehicles (AGVs), are widely applied in manufacturing factories and warehouses. AGVs can support the on-site material logistics, and robotic arms are used for product assembly both in fixed-position assembly and flow-line assembly, which also have the potential for assembly tasks on construction site. Unmanned Aerial Vehicle (UAV) or drone is used for monitoring in construction projects in terms of several aspects, such as safety supervision, site surveys, visual detection, and infrastructure measurement. UAV can capture the real-time images or videos of the target objects through a flexible and quick movement mode. Compared to other monitoring technologies, such as RFID or GPS, UAV owes several advantages, including the high portability, simple operation, real-time response, and high mobility (Tian et al., 2021). The application of UAVs to collect data and monitor the construction project has potential to be more concise, less expensive, and easier to operate than conventional methods (J. Wu et al., 2021). For H-Sync with coordinated resource utilization, robotics automates tasks like logistics and bricklaying, reducing human labor requirements and enabling coordinated execution of complex operations with minimal human intervention. Robots transmit real-time data on their status and operations to digital twins, enabling remote monitoring and control. Decisions made in the cyber space can then be executed by robots in the physical space to achieve the C2P control bridge.

Based on the mentioned above information and automation technologies, a digital twin-based systematic framework for smart construction management has been established, as shown in Fig. 11. This framework consists of five layers from infrastructure to service-oriented modules, including the physical layer, sensing layer, interoperation module, digital layer, and service layer. Within these functional structures, multiple stakeholders become vital players in the future construction management, underlining the human-centricity characteristic. This cyber-physical integrated and interoperated environment paves the way for the realization of digitalization, automation, and intelligence in current Construction 4.0, and the resilience, sustainability, and human-centricity in future construction management.

5.2. Digital twin-enabled reshaped management paradigm for future construction

The paradigm shift inherent in future upgrading Construction 4.0 necessitates a synchronized approach that encapsulates both the semantic and geometric attributes and actions based on the proposed roadmap and orthogonally synchronized digital twin model combining H-Sync and V-Sync. This approach furnishes real-time perception, dynamic regulation, and information dissemination services for multi-objective optimization (Sacks et al., 2020; Tao and Qi, 2019). A confluence of pioneering technologies integrated with digital twins serves to optimize project planning, operation scheduling, resource allocation, waste reduction, and system deployment. This amalgamation of methods is reshaping construction management within the framework of future construction (Agrawal et al., 2022; Pan and Zhang, 2021a). Real-time n-dimensional information, including factors such as status, location, quality, cost, worker safety, and environmental impact, can be unveiled and analyzed through high-fidelity digital twins. This process facilitates managers and provides support for operators to safely execute their daily tasks with enhanced accuracy, timeliness, visibility, and efficiency (Cai et al., 2019; Jiang et al., 2022). The upgraded digital twin-enabled construction management chiefly exhibits the following directions.

5.2.1. Direction 1: distributed optimization

In future management, distributed optimization involves the decentralization of data processing, decision-making, and task execution across various entities and subsystems. This aims to maximize efficiency and effectiveness, synchronized and merged through the H-Sync mechanism, based on the Divide and Conquer (D&C) concept. The digital twin facilitates distributed optimization by dividing construction project aspects into multiple subtasks. These subtasks are assigned to different nodes for processing, which maximizes optimization goals through real-time data sharing and collaboration under H-Sync in the synchronized digital twin mechanism. The advantages of distributed optimization based on D&C for future construction management are as follows.

(a) *Improve efficiency*: In complex construction projects, by dispersing data processing, decision-making, and task execution into

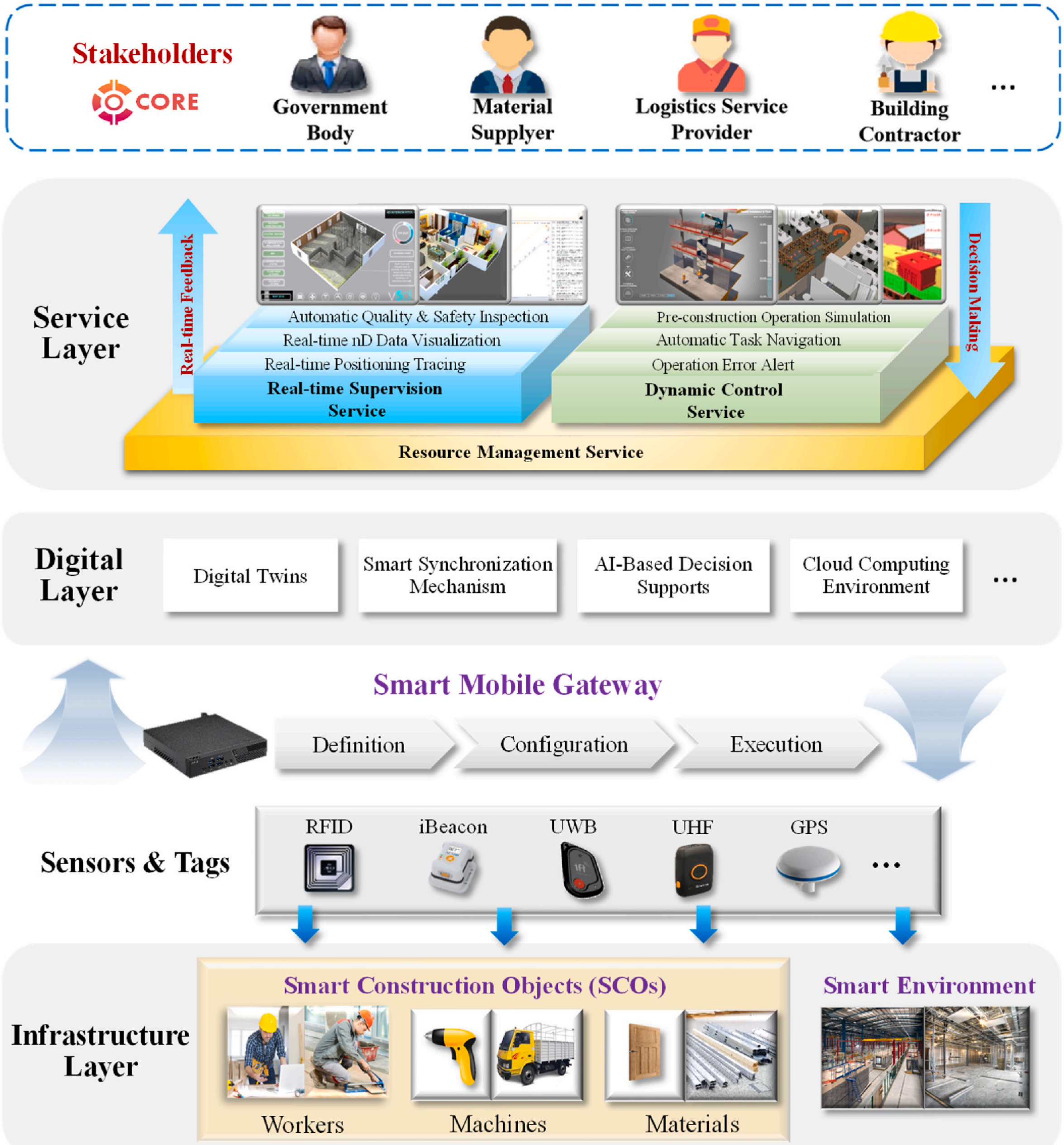

Fig. 11. Digital twin-based technical framework for future construction management.

different entities and subsystems, multiple optimization processes can be carried out simultaneously, accelerating project execution speed.

(b) *Optimize resource utilization*: Assigning tasks to the most suitable nodes can fully utilize the capabilities and advantages of each node. Different nodes can share information and experience, collaborate with each other, and achieve the optimized results.

(c) *Enhance robustness*: Distributed optimization mechanism can enhance the robustness and reliability as other nodes can take over tasks in case of one node failure or malfunction, ensuring the normal progress of the entire project.

(d) *Improve flexibility and adaptability*: By reassigning tasks and resources, nodes can self-adjust according to new constraints or optimization objectives to satisfy the dynamic variations in the project. The flexibility and adaptability enable the system to better cope with uncertainties and disruptions, guaranteeing the stability of the construction system.

5.2.2. *Direction 2: enhanced multi-domain collaboration and synchronization*

In construction projects, diverse entities with unique functionalities demand interdisciplinary collaboration. Stakeholders, equipped with cross-domain knowledge, target benchmarks like digitalization, automation, intelligence, resilience, sustainability, and human-centricity. Crucially, human-centric management is emphasized in the H-Sync. The synchronized digital twin model fosters collaboration by allowing stakeholders to share digital twins, facilitating expertise, knowledge, and resource contributions across domains. This collaborative effort spans the entire project lifecycle, aiding transdisciplinary stakeholders in focusing on core issues within each domain. Under SDT model, diverse technologies seamlessly integrate and collaborate, enabling real-time monitoring and dynamic control. A ubiquitous digital twin method, with enhanced generality, proves beneficial. It involves selectively simplified descriptions of different objects for a high-fidelity V-Sync, considering spatial scales, progress stages, and functional emphases.

This approach significantly improves efficiency during interdisciplinary collaboration in future construction, aligning with scientific rigor.

5.2.3. Direction 3: transition from stochasticity to determinacy

In traditional optimization systems, stochastic functions often estimate parameters, treating the arrival time of system input and corresponding processing time as independent, identically distributed, and non-negative random variables. This stochastic nature introduces higher computational complexity in both time and space dimensions. However, the advanced capabilities of digital twins have reached a stage where stochastic parameters can be transformed into deterministic inputs using real-time data from production, logistics, and on-site operations in construction management. These real-time data from digital twins offer stakeholders immediate cyber-physical visibility and traceability under the V-Sync mechanism. This enables the determination and adjustment of schedules for resources and operations within more acceptable computational time complexities (*better lower than* $O(n^2)$). The availability of real-time data simplifies decision-making for managers and workers, providing a clear understanding of the current situation and anticipation of future developments in the project. This transition towards deterministic parameters significantly enhances the decision-making process. By integrating digital twins into synchronous systems, managers and workers can gain insights into the current status and future projections of construction projects. This facilitates quicker and more informed decision-making based on deterministic parameters, ultimately streamlining operations, and boosting efficiency in future construction management.

5.2.4. Direction 4: improved dynamics and resilience in stochastic circumstances

Traditional optimization models, exemplified by Mixed-Integer Linear Programming (MILP) or metaheuristics algorithms, efficiently yield theoretically optimal solutions with enhanced precision and efficiency (Paul and Anand, 2015; Silva and Camponogara, 2014; Zhang et al., 2015). However, these models encounter challenges in adapting to swift changes in attributes and constraints under rolling time windows in a digital twin environment, resulting in outdated rearrangements. During rolling time windows, parameters, constraints, and objective functions in the computational process may swiftly change, encompassing aspects such as priority, deadline, and resource requirements. Taking Non-dominant Sorting Genetic Algorithm-II (NSGA-II) as an illustration, on-site disturbances pose difficulties in updating the population and maintaining the Pareto front, rendering timely responses challenging. Objective functions play a pivotal role in traditional optimization models, generating a static blueprint for task allocation and scheduling. In the realm of future construction management within a digital twin system, the optimization model shifts its focus to real-time occurrences during actual construction processes. Optimal decisions, informed by real-time data collected from digital twins at each current time window, facilitate near-optimal performance through global regulation. This transformative approach enhances project resilience by adeptly considering real-time variations in different parameters.

In conclusion, the evolving landscape of construction management heralds a revolutionary era marked by Construction 4.0, where the amalgamation of digital twins and cutting-edge technologies reshapes the industry. The new paradigm not only champions distributed optimization for accelerated project execution but also champions enhanced multi-domain collaboration, transcending traditional boundaries, and fostering innovation across diverse functionalities. The strategic shift from stochastic approaches to deterministic ones, leveraging real-time data from digital twins, not only simplifies decision-making but also introduces a novel level of cyber-physical visibility and traceability. Furthermore, the emphasis on improved dynamics and resilience in stochastic circumstances signifies a departure from conventional optimization models, ushering in a real-time decision-making era that adeptly navigates dynamic variations for near-optimal project performance. This visionary approach, encapsulated in the conceptual diagram, propels construction management into an era of interconnected, adaptive, and technologically empowered efficiency.

6. Final remarks

This paper conducts an analysis of the foundational elements and developmental pathways for the prospects of intelligent management modes in future construction epochs, leveraging advancements in digital twins. Digital twin technology has experienced rapid development since 2017, with an increasing growth rate each year. Quantitative results suggest that digital twins will continue to garner attention from both academic and industrial fields in the foreseeable future. Engineering and computer science are the two domains most significantly influenced by digital twin development. As a fundamental component of engineering, construction is progressively being reshaped by digital twins, with existing foundational technologies effectively paving the way for digital twin-aided management modes. Through an examination of current research and the proposal of new insights, this study makes three significant contributions.

(1) This study offers a thorough review of the present state of Construction 4.0, serving as the foundational basis for the forthcoming era. Digital Twins and Cyber-Physical Systems (CPS) are integral elements within the Construction 4.0 context, achieving real-time cyber-physical integration and interoperation at both the construction resource level and process levels.
(2) This study briefly defines the core of future construction management is the orthogonal synchronization and formulates the Synchronized Digital Twin (SDT) model with regular expression, encompassing two types of synchronizations: Horizontal Synchronization (H-Sync) and Vertical Synchronization (V-Sync). This research focuses on the orthogonal synchronization, which mainly considers the multi-source collaboration under the mechanism of cyber-physical interoperation in the context of Construction 4.0. V-Sync refers to the real-time cyber-physical bidirectional synchronization, which facilitates connection and interoperation between physical resources and operations with their corresponding digital twins. H-Sync entails coordinated interactions among different construction resources, operations, human factors, and energy sources, with the intent to conduct appropriate operations using suitable resources and energy at the optimal time and location, in a manner that promotes human wellbeing.
(3) This study discusses the roadmap framework for the future construction management, which extends beyond mere application of technologies under a cyber-physical integration context. The key element of future construction is human centricity, which is supported by sustainability and resilience. It also considers the upgrading of the business model and organizational structure to enhance stakeholder-worker wellbeing, promote collaboration and cooperation at various stages, and foster environmental sustainability for the multi-domain balance.

Except the contributions completed by this paper, several limitations are also presented as follows. First, the proposed roadmap and SDT model outlined in this paper serve as a conceptual framework for future construction management. However, it is crucial to acknowledge that these concepts require thorough testing and validation in real-world scenarios. Future research should focus on practical implementations and empirical studies to assess the effectiveness and feasibility of the proposed roadmap and SDT model in diverse construction contexts. Second, while this research provides a comprehensive roadmap for future construction management, it does not delve deeply into the integration of AI with digital twins, which is a pivotal aspect of transformative advancements in the field. AI has the potential to revolutionize construction management by automating tasks, optimizing processes, and enhancing decision-making. Future studies should explore and elaborate on the synergies between AI and digital twins to harness their combined capabilities for more intelligent and efficient construction practices. Third, current research trends also emphasize a holistic approach to smart cities and infrastructures management, shifting the focus from merely constructing new buildings to the comprehensive management of existing structures. There is a compelling need to explore how advanced technologies can contribute to maintaining, operating, and managing current urban infrastructures. Future studies should delve deeper into methodologies, technologies, and strategies for prolonging the lifespan, optimizing performance, and ensuring the resilience of infrastructure within the broader context of smart city development.

This study offers valuable insights for various stakeholders in the construction industry, including architects, engineers, project managers, and policymakers. The findings and recommendations presented in this paper can inform decision-making processes related to the adoption and implementation of digital twin in construction projects. Furthermore, by understanding the potential benefits and challenges associated with digital twin-aided management modes, practitioners can develop strategies to enhance project efficiency, minimize risks, and improve overall project outcomes. Therefore, this study holds relevance for anyone involved in the planning, design, construction, and operation of built environments, as it provides a roadmap for leveraging digital twins to advance the construction industry into a more sustainable, resilient, and human-centric future.

CRediT authorship contribution statement

Yishuo Jiang: Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shuaiming Su:** Methodology, Data curation, Conceptualization. **Shuxuan Zhao:** Validation, Software, Methodology. **Ray Y. Zhong:** Supervision, Project administration, Funding acquisition, Conceptualization. **Waishan Qiu:** Writing – review & editing. **Miroslaw J. Skibniewski:** Supervision, Methodology, Conceptualization. **Ioannis Brilakis:** Supervision, Methodology, Conceptualization. **George Q. Huang:** Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors of "Digital Twin-Enabled Synchronized Construction Management: A Roadmap from Construction 4.0 towards Future Prospect" for *Developments in the Built Environment* declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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