

Facilitating Construction 5.0 for smart, sustainable and resilient buildings: opportunities and challenges for implementation

Smart and
Sustainable Built
Environment

729

Ibrahim Yitmen and Amjad Almusaed

*Department of Construction Engineering and Lighting Science,
Jönköping University, Jönköping, Sweden, and*

Sepehr Alizadehsalehi

Project Management Program, Northwestern University, Evanston, Illinois, USA

Received 16 April 2024
Revised 25 August 2024
Accepted 27 September 2024

Abstract

Purpose – The concept of Construction 5.0 has emerged as the next frontier in construction practices and is characterized by the integration of advanced technologies with human-centered approaches, sustainable practices and resilience considerations to build smart and future-ready buildings. However, there is currently a gap in research that provides a comprehensive perspective on the opportunities and challenges of facilitating Construction 5.0. This study aims to explore the opportunities and challenges in facilitating Construction 5.0 and its potential to implement smart, sustainable and resilient buildings.

Design/methodology/approach – The structural equation modeling (SEM) method was used to evaluate the research model and investigate the opportunities and challenges related to Construction 5.0 in its implementation for smart, sustainable and resilient buildings.

Findings – The results show that adopting human-centric technology, sustaining resilience and maintaining sustainability in the architecture, engineering and construction (AEC) industry seizes the opportunities to overcome the challenges for facilitating Construction 5.0 in the implementation of smart, sustainable and resilient buildings.

Practical implications – The AEC industry facilitating Construction 5.0 has the potential to redefine the future of construction, creating a built environment that is not only intelligent, sustainable and resilient but also deeply connected with the well-being and values of the communities it serves.

Originality/value – The research illuminates the path forward for a holistic understanding of Construction 5.0, envisioning a future where smart, sustainable and resilient buildings stand as testaments to the harmonious collaboration between humans and technology.

Keywords Construction 5.0, Smart, Sustainable, Resilient, Buildings, Human-centric technology, SEM, AEC industry

Paper type Research paper

1. Introduction

The emergence of Industry 5.0 is characterized by its emphasis on integrating people, procedures, technology, and information, focusing on human-centricity, sustainability, and resilience (Maddikunta *et al.*, 2022; Xu *et al.*, 2021). As the Architecture, Engineering, and Construction (AEC) sector continues to evolve, there is a growing need to explore how the principles of Industry 5.0 can be integrated into construction practices. The Industry 5.0 paradigm undoubtedly offers considerable promise in integrating building construction processes and technology. To optimize the advantages derived from the integration of diverse elements, it is essential for research to proficiently organize, reassess, and contextualize the



© Ibrahim Yitmen, Amjad Almusaed and Sepehr Alizadehsalehi. Published by Emerald Publishing Limited. This article is published under the Creative Commons Attribution (CC BY 4.0) licence. Anyone may reproduce, distribute, translate and create derivative works of this article (for both commercial and non-commercial purposes), subject to full attribution to the original publication and authors. The full terms of this licence may be seen at <http://creativecommons.org/licenses/by/4.0/legalcode>

Smart and Sustainable Built Environment
Vol. 15 No. 2, 2026
pp. 729-764
Emerald Publishing Limited
2046-6099
DOI 10.1108/SASBE-04-2024-0127

interplay of developing practices, ideas, approaches, and technical instruments (Ikudayisi *et al.*, 2023). Ikudayisi *et al.* (2023) suggests future studies of Construction 5.0 involving human-centric technology, resilience, and sustainability in the AEC industry. Marinelli (2023) investigates the path toward human-robot collaboration in Construction 5.0, emphasizing the distinct challenges and suggesting new focuses. Zizic *et al.* (2022) pointed out the significance of people, organizations, and technology as enablers of their application for Industry 5.0. Leng *et al.* (2022) outlined the evolutionary path of Industry 5.0, providing a concise summary of its meaning, structure, supporting technologies, and associated challenges. Mourtzis *et al.* (2022) examined the pivotal technologies that will propel the advent of Operator 5.0 and underscored the primary obstacles in achieving this transformation for Industry 5.0. Yitmen *et al.* (2023) offered a valuable contribution by introducing the idea of Construction 5.0, which centers on a technologically advanced society and highlights the need for collaboration between humans and robots.

In recent years, the construction industry has been undergoing a transformative shift with the advent of Industry 5.0, which places significant emphasis on human-centric approaches, sustainability, and resilience (Fraga-Lamas *et al.*, 2024). The integration of these principles into the AEC sector is vital for advancing smart, sustainable, and resilient building practices. Human-centric technology plays a crucial role in enhancing worker safety and productivity in Industry 5.0, while the evolution of Industry 5.0 brings implications for the AEC sector, particularly in integrating advanced technologies like Digital Twins (DT) and the Internet of Things (IoT) with traditional construction practices (Musarat *et al.*, 2023).

The concept of Construction 5.0 presents a framework that emphasizes the harmonious collaboration between humans and robots within sustainable ecosystems (Adel, 2023). This framework aligns with the broader goals of Industry 5.0 and addresses the specific needs of the construction industry, where human-centric technology and resilience are essential for ensuring the successful implementation of smart, sustainable, and resilient buildings (Sharma, 2024). The challenges and opportunities presented by human-robot collaboration in the construction industry underscore the need for new approaches that prioritize human welfare alongside technological advancement.

The sustainability aspect of Construction 5.0 has garnered significant attention in the literature, emphasizing the role of sustainability in achieving long-term environmental goals within the AEC sector (Baig and Yadegaridehkordi, 2024). The adoption of circular economy principles and the integration of green technologies are advocated to minimize the environmental footprint of construction activities. Additionally, resilience and sustainability are operationalized within construction projects to enhance their adaptability to changing environmental conditions and ensure their longevity.

During the rapidly evolving landscape of Industry 5.0, a profound shift towards human-centricity, sustainability, and resilience has taken center stage, presenting an unprecedented opportunity to redefine the future of the AEC sector. As we navigate the unexplored frontier of Construction 5.0, it becomes imperative to not only unravel the intricacies of its integration with Industry 5.0 but also to chart a course that optimizes the potential synergies. This study ventures beyond the well-trodden paths of current research by focusing on the dynamic interplay between human-centric technology, resilience, and sustainability within the AEC industry, shedding light on the transformative possibilities that lie at the intersection of societal needs and technological advancements (Ikudayisi *et al.*, 2023). In doing so, we not only bridge the existing gap in research but also lay the foundation for a holistic understanding of Construction 5.0, envisioning a future where smart, sustainable, and resilient buildings stand as testaments to the harmonious collaboration between humans and technology.

The integration of Construction 5.0 with the three pillars of sustainability—economic, environmental, and social—adds a crucial dimension to our exploration of the AEC sector's future. By aligning our investigation with these pillars, we aim to underscore the transformative potential of Construction 5.0 in addressing broader societal challenges and

contributing to sustainable development goals. Specifically, this study will delve into how Construction 5.0 can enhance economic efficiency, minimize environmental impact, and foster social inclusivity within the AEC industry. The salient sustainable development goals (SDG 9 and SDG 11) will serve as guiding frameworks, allowing us to evaluate the immediate benefits and long-term impacts of Construction 5.0 in a comprehensive and globally relevant manner. This study is the continuation of the research performed by [Yitmen *et al.* \(2023\)](#) investigating the causal relationships among enablers of the Construction 5.0 paradigm focusing on the integration of Operator 5.0 and Society 5.0 with Human-Centricity, Sustainability, and Resilience. Building on [Yitmen *et al.* \(2023\)](#)'s model, and system of Construction 5.0, the study is the first research to investigate the relationships between human-centric technology, resilience, sustainability, and present the opportunities, and challenges in implementing Construction 5.0 for smart, sustainable, and resilient buildings using SEM method.

The paper is structured as follows: [Section 2](#) provides a theoretical foundation for Construction 5.0 and presents an overview of its structure. [Section 3](#) provides a comprehensive explanation of the methodology used in this study. It includes a detailed discussion of the structural equation modeling (SEM) model, the process of hypothesis formulation, the measurement methods, and the structural model's assessment. [Section 4](#) of the paper explores the theoretical contributions, limitations, and prospective areas for further study. The manuscript is concluded in the last part, namely [Section 5](#).

2. Theoretical background

The concepts constituting Construction 5.0, including human-centric technology, resilience, and sustainability are continuously evolving. It's crucial to emphasize this novelty and provide contextualization within the current landscape of technological advancements and evolving industrial paradigms. Below is a deeper look at each aspect.

2.1 Human-centric technology for Construction 5.0

Industry 5.0 advocates for incorporating technologies and processes that prioritize human-centric principles. This approach emphasizes human intelligence within inclusive work settings, stimulating innovation and facilitating customization ([Maddikunta *et al.*, 2022](#); [Xu *et al.*, 2021](#); [Ikudayisi *et al.*, 2023](#)). To attain flexibility, adaptability, and the capacity to withstand disruptions, factories must adopt a human-centered manufacturing approach ([Fonda and Meneghetti, 2022](#); [Nguyen Ngoc *et al.*, 2022](#); [Wang *et al.*, 2022](#)). This approach enhances worker well-being and safety by facilitating collaboration between humans and robots and reduces monotonous tasks ([Kadir and Broberg, 2021](#); [Colla *et al.*, 2021](#)). Human-centered manufacturing emphasizes aspects, emphasizing their requirements and concerns over technological factors ([Xu *et al.*, 2021](#)). Within the realm of industrial work systems, the integration of a critical human-centered approach combines the principles of human factors and ergonomics. This integration aims to improve the system's overall efficacy and promote employee satisfaction while also addressing the problems posed by social technologies ([He *et al.*, 2017](#)).

Human-Centric Technology for Construction 5.0 revolves around placing human needs, experiences, and capabilities at the forefront of technological innovation within construction processes. It's a shift from technology-driven solutions to technology that adapts to and enhances human capabilities and well-being. This includes advancements like human-machine collaboration, augmented reality interfaces for workers, and intelligent systems that support rather than replace human skills. As a result, forthcoming research endeavors encounter a notable obstacle in achieving a harmonious equilibrium between physicality and automation. This necessitates the integration of both Building Information Modeling (BIM) and non-BIM elements, harnessing the potential of both information technology (IT) and

non-IT platforms, and establishing a connection between the tangible and virtual domains to ensure seamless integration in the design, construction, and delivery phases. Future research endeavors must explore various themes to integrate within AEC industry. These themes encompass the exploration of BIM and Digital Twin (DT) in the context of integrated design, the utilization of cloud computing for combined design purposes, the incorporation of collaborative robots (cobots) and 4D printing in modular integrated construction (MiC), the implementation of mass customization within MiC, the application of blockchain technology and smart contracts, as well as the utilization of big data analytics in the supply chain (Ikudayisi *et al.*, 2023).

2.2 Resilience for Construction 5.0

The concept of Industry 5.0 places significant emphasis on the need for industrial production to possess the capability to endure crises and proficiently manage interruptions to vital infrastructure (Xu *et al.*, 2021). In the context of Construction 5.0, resilience refers to the industry's ability to adapt and recover from challenges or disruptions. This could involve incorporating technologies that enable quick adjustments to changing conditions, robust planning strategies, and systems that anticipate and mitigate risks. It also encompasses the capacity to bounce back from unexpected setbacks and maintain continuous operations. In recent years, the AEC industry has shown remarkable resilience. Companies that embrace and adapt to new technologies, especially during the pandemic, are positioning themselves to outpace their competitors (Kor *et al.*, 2023). Given the AEC industry's role in building crucial infrastructure, attaining resilience via integrating design, construction, and delivery is paramount. Future endeavors should prioritize the development of pragmatic roadmaps and frameworks aimed at augmenting stability in diverse project categories and across varying geographical settings. The integration of resilience training should be established as a customary practice within the industry. One potentially effective strategy is the development of an integrated climate index vulnerability index and the subsequent implementation of adaptation techniques and mitigation measures. The successful implementation of this initiative necessitates the comprehensive collection, analysis, documentation, regular updating, and practical application of data throughout all stages of the project. Promising avenues for research encompass integrating design and planning processes to enhance project resilience, recovery, and rebuilding efforts. Investigating multi-sourcing strategies, implementing the MiC system to optimize reconstruction efficiency, employing integrated risk contracting, utilizing big data analytics for resilience planning, and leveraging BIM to augment resilience planning are all areas worthy of academic exploration (Ikudayisi *et al.*, 2023).

2.3 Sustainability for Construction 5.0

While sustainability studies in the AEC sector have gained considerable attention in the past 2 decades (Ikudayisi *et al.*, 2023), the emergence of the Industry 5.0 paradigm demands a more comprehensive and integrated approach. The focus on sustainability in Construction 5.0 is about adopting practices that minimize environmental impact while ensuring long-term viability. This includes eco-friendly construction materials, energy-efficient designs, waste reduction strategies, and embracing green technologies. It also involves creating structures and systems that can withstand the test of time while minimizing their ecological footprint. Sustainability in this context focuses on optimizing resource efficiency, reducing greenhouse gas emissions, and utilizing renewable and non-polluting resources. Previous research (Ikudayisi *et al.*, 2023) has highlighted the significance of integrated procedures (IPs) in achieving sustainability within the AEC sector, making sustainability studies a prominent area of research for scholars. Considering the interdependence of the AEC (Architecture, Engineering, and Construction) industry with various sectors, including manufacturing, energy, chemical, and agriculture, it is imperative to investigate novel technologies such as blockchain, DT, and big data analytics. These tools can effectively facilitate information

integration and promote collaboration among these industries. Consequently, adopting these technologies can contribute to advancing sustainability and circular economy objectives within the AEC industry. Focus was given to modern circularity, cleaner production, and sustainability as key advantages of Green-IoT adoption, aligning with the United Nations' Sustainable Development Goals (UN-SDGs) (Ullah *et al.*, 2024). The sharing of large-scale data among many stakeholders within these businesses can significantly enhance the sustainability results of the supply chain (Ikudayisi *et al.*, 2023).

2.4 Opportunities for facilitating Construction 5.0

Opportunities for facilitating Construction 5.0 that appeared in the literature are as follows:

Advancements in Technology: Construction 5.0 harnesses intelligent, cutting-edge technologies like DT, IoT, AI, Big data analytics, Blockchain, and Cobots to optimize construction processes and enhance building performance. These technologies enable real-time data exchange, predictive maintenance, and efficient resource management (Maddikunta *et al.*, 2022; Leng *et al.*, 2022; Yitmen *et al.*, 2023).

The concept of Stimulating Operator 5.0 revolves around two primary elements. Firstly, it places significant emphasis on fostering “self-resiliency” within the workforce, recognizing their inherent vulnerability. Secondly, it prioritizes attaining “system resiliency” within manufacturing environments, where human operators and machines collaborate to ensure optimal system performance. Construction 5.0 is anticipated to facilitate a harmonious collaboration between human workers and autonomous equipment. The future workforce will be able to sense and understand human intents and preferences, hence becoming independent in their decision-making processes. Given the understanding that people have the comprehensive comprehension and productive powers of their robotic counterparts, it is anticipated that humans would engage in collaborative endeavors with robots devoid of trepidation. The synergistic partnership between human workers and mechanical systems will result in a significantly optimized production process characterized by enhanced value creation, heightened reliance on automation, and diminished waste generation and cost expenditures (Maddikunta *et al.*, 2022; Leng *et al.*, 2022; Yitmen *et al.*, 2023).

Motivating Society 5.0: Viewed through a socio-technical system perspective, the industry's transformation and societal evolution are mutually reinforcing (Huang *et al.*, 2022). Society 5.0 underscores the harmonious fusion of virtual and tangible realms to achieve equilibrium between economic advancement and resolving diverse societal concerns (Kravets *et al.*, 2021). This is accomplished by providing customized products and services that cater to a wide range of latent needs, irrespective of geographical location, age, gender, or language. Society 5.0 anticipates the revolutionary integration of information technology inside many industries and aims to alter human living environments and behaviors. The vision at hand encompasses four fundamental concepts: “a society centered around human beings,” “the fusion of cyberspace and physical space,” “a society reliant on knowledge,” and “a society driven by data.” (Maddikunta *et al.*, 2022; Leng *et al.*, 2022; Yitmen *et al.*, 2023).

Circular economy: Construction 5.0 encourages the adoption of circular economy principles, promoting the reuse, refurbishment, and recycling of building materials. Digital interfaces and blockchain technology facilitate the exchange and tracking of materials, enabling a more sustainable and circular approach to construction. Life Cycle Assessment (LCA), in conjunction with intelligent goods, offers verifiable data to bolster the attainment of net zero carbon emissions and circular economy objectives. The given sequence is (Ikudayisi *et al.*, 2023; Marinelli, 2023; Yitmen *et al.*, 2023; Turner *et al.*, 2022).

Sustainable Building Practices: Construction 5.0 focuses on implementing sustainable building practices, which include several aspects like green building certifications, energy-efficient design strategies, integration of renewable energy sources, and responsible procurement of materials. By adopting these practices, buildings can significantly reduce their environmental footprint and contribute to a greener future (Yitmen *et al.*, 2023).

Resilience and Adaptability: Resilience is a critical component of Construction 5.0, focusing on building structures and systems that can withstand natural disasters and adapt to changing environmental conditions. Resilient buildings are designed to minimize damage and quickly recover from disruptions (Yitmen *et al.*, 2023; Gholami *et al.*, 2021; Roostaie and Nawari, 2022).

Smart Building Features: Construction 5.0 promotes incorporating smart building features like automated systems, IoT-enabled sensors, and data analytics for optimizing energy consumption, comfort, and safety. Smart buildings enhance occupant experience and improve operational efficiency (Ikudayisi *et al.*, 2023; Yitmen *et al.*, 2023; Almusaed and Yitmen, 2023).

2.5 Challenges in facilitating Construction 5.0

Challenges in facilitating Construction 5.0 that appeared in the literature are as follows:

High Initial Costs and Funding: Implementing advanced technologies and sustainable practices often involves higher upfront costs, which can be a barrier for many construction projects. However, long-term operational savings and increased building value can offset these costs. Construction 5.0 is predicted to incorporate extensive customization facilitated by interconnected devices, collaboration between humans and robots, and significant technological advancements. These advancements would require substantial investments from local authorities and the leading organizations involved. However, developing nations with competing priorities and organizations focused on short-term gains may view these costs and funding requirements as significant obstacles, making them hesitant to embrace Construction 5.0 (Xu *et al.*, 2021; Fukuda, 2020; Mukherjee *et al.*, 2023).

Skilled Workforce: As robots handle repetitive daily tasks, humans must possess specialized skills for managing exceptional scenarios, creative tasks, and design. This shift in job requirements may create opportunities for new roles that currently do not exist, leading to a potential shortage of skilled workers. Effective trainers and training programs will be necessary to resolve this challenge. Skills development among construction stakeholders has become increasingly critical for the successful implementation of Construction 4.0 in recent years (Siriwardhana and Moehler, 2024). As Construction 5.0 is still in its infancy of development, it is essential to note that the government, society, and organizations may not be completely prepared for this transition (Maddikunta *et al.*, 2022; Xu *et al.*, 2021; Mukherjee *et al.*, 2023; Breque *et al.*, 2021; Demir *et al.*, 2019).

Data Security and Privacy: Industry 5.0 seeks to bridge the gap between the physical and cyber worlds by incorporating many interconnected systems, processes, machinery, devices, platforms, and nodes [23,26]. Even though these elements create a dense network, businesses must prioritize data security and prevent any intrusions while maintaining service and operational efficiency (Maddikunta *et al.*, 2022; Mukherjee *et al.*, 2023). Companies must, therefore, address authentication, integrity, access control, and auditing security issues to effectively implement Construction 5.0 (Mukherjee *et al.*, 2023; Liyanage *et al.*, 2020).

Regulatory and Policy Frameworks: Enforcing regulations pertinent to specific advances in Industry 5.0 becomes essential. It is anticipated that Construction 5.0 will introduce novel and intelligent operational methods, including human-robot collaboration, 6G technology, digital twins, additive manufacturing, drone technology, connected intelligent devices, and numerous systems (Maddikunta *et al.*, 2022; Mukherjee *et al.*, 2023). To effectively manage each of these innovations, it is necessary to enact new laws and regulations that reflect the overall orientation of ecosystems. These regulations should cover aspects such as human-robot coworking and differentiate between different categories of robotics and machinery, such as drones and robots (Mukherjee *et al.*, 2023; Demir *et al.*, 2019). In addition, explicit policies regarding technological and ecosystem innovation must be articulated, with elements of agility and flexibility (Xu *et al.*, 2021; Mukherjee *et al.*, 2023).

Scalability: Scalability refers to a system's ability to handle a significant increase in workload without compromising its performance. In the context of Construction 5.0, where there are multiple interconnected devices and applications, it is essential for systems to be capable of scaling up to meet the growing demand. This becomes especially crucial in co-working environments where humans and robots are interconnected through the internet and work together seamlessly (Maddikunta *et al.*, 2022; Mukherjee *et al.*, 2023; Sharma *et al.*, 2022).

Acceptance and Adaptability: The resistance towards adopting robots and other machines in the workplace poses a considerable barrier. The fear of machines replacing human workers in their current roles may result in a reluctance to adapt (Xu *et al.*, 2021; Mukherjee *et al.*, 2023; Demir *et al.*, 2019).

Ethical Concerns: The emergence of ethical concerns in human-robot co-working revolves around instilling ethical principles within machines. Ethical dilemmas may also surface when utilizing AI and Machine Learning (ML), particularly if robots replace humans in routine tasks (Maddikunta *et al.*, 2022; Mukherjee *et al.*, 2023; Demir *et al.*, 2019; Stahl, 2021; Vesnic-Alujevic *et al.*, 2020).

Table 1 provides a synthesis of the most critical opportunities and challenges identified in the literature for facilitating Construction 5.0. The table focuses on those aspects most frequently cited across multiple studies, representing a distilled overview rather than an exhaustive list. This approach allows for highlighting key areas of concern while acknowledging that other challenges and opportunities may exist depending on the specific context of each construction project. The selection process for these items was rigorous, ensuring they reflect the most significant and commonly discussed themes in the current literature.

3. Materials and methods

The overview of the research methodology involving theoretical and practical approaches is depicted in Figure 1.

3.1 SEM model and hypothesis development

Significant positive relationships between Human-centric technology, Resilience, Sustainability, Opportunities, Challenges in facilitating Construction 5.0 and Smart, Sustainable, and Resilient Buildings have been shown by the literature in Section 2. The hypotheses were developed based on an extensive review of the existing literature in the fields of human-centric technology, resilience, sustainability, and their roles in the AEC industry. Each hypothesis reflects the findings of prior studies who demonstrated the impact of human-centric approaches on technological adoption, and linked resilience strategies to successful construction outcomes. The constructs and their interrelationships were identified through a systematic synthesis of theoretical frameworks and empirical evidence, ensuring that the hypotheses are well-founded and relevant to the context of Construction 5.0.

The relationships of the dependent variables (Opportunities, Challenges, and Smart Sustainable and Resilient Buildings) and independent variables of Human-centric technology, Resilience, and Sustainability are recognized to describe and highlight the theory underlying the relationships and to state the directions of their relationships. The most important factors of Human-centric technology, Resilience, Sustainability, Opportunities, Challenges in facilitating Construction 5.0, and Smart Sustainable and Resilient Buildings, as identified from the existing literature, are illustrated in Table 1.

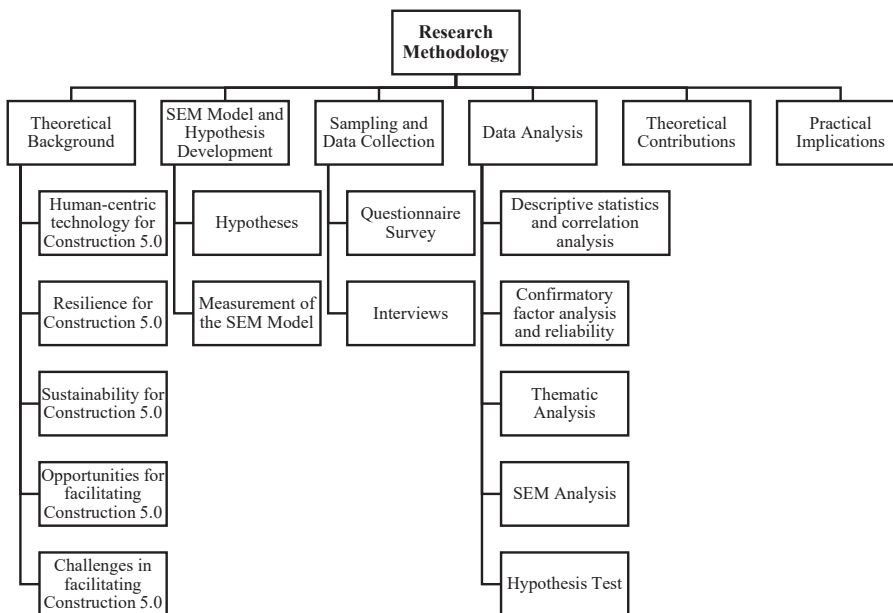
Table 1 provides a synthesis of the most critical opportunities and challenges identified in the literature for facilitating Construction 5.0. The table focuses on those aspects most frequently cited across multiple studies, representing a distilled overview rather than an exhaustive list. This approach allows for highlighting key areas of concern while acknowledging that other challenges and opportunities may exist depending on the specific

Table 1. Summary of literature involving the opportunities and challenges of Construction 5.0 for implementing smart, sustainable, and resilient buildings

No	Constructs and indicators	References
1	<i>Human-centric technology for Construction 5.0</i>	
1.1	Machines and robots not replacing humans in the industry	Yitmen <i>et al.</i> (2023), Ikudayisi <i>et al.</i> (2023), Zizic <i>et al.</i> (2022), Mourtzis <i>et al.</i> (2022), Fonda and Meneghetti (2022), Nguyen Ngoc <i>et al.</i> (2022), Wang <i>et al.</i> (2022), Kadir and Broberg (2021), Colla <i>et al.</i> (2021), He <i>et al.</i> (2017), Huang <i>et al.</i> (2022), Kravets <i>et al.</i> (2021), Nahavandi (2019), Lu <i>et al.</i> (2021), Papetti <i>et al.</i> (2020), Lu <i>et al.</i> (2022)
1.2	Necessity of human involvement for achieving automation and digitization	
1.3	Prioritization of human needs and interests as the foundation of the production process	
1.4	Demand of intelligent robots understanding the interconnected relationships between humans and machines in unstructured environments	
1.5	Autonomously ensuring the security and stability of communication networks that serve as social infrastructure	
2	<i>Resilience for Construction 5.0</i>	
2.1	Re-thinking existing working methods and approaches	Yitmen <i>et al.</i> (2023), Xu <i>et al.</i> (2021), Zizic <i>et al.</i> (2022), Leng <i>et al.</i> (2022), Mourtzis <i>et al.</i> (2022), Ivanov (2023), Romero and Stahre (2021)
2.2	Reducing the vulnerability of supply chains	
2.3	Focusing on the ability of firms to cope with external uncertainties	
2.4	Focusing on the resilience of a wider range of industrial systems	
2.5	Technology systems and solutions prioritizing stability over resilience and providing more prevalent and mass-automation solutions	
3	<i>Sustainability for Construction 5.0</i>	
3.1	Implementing the sustainable construction vision regarding the decentralized connection of socialized production resources and products to deliver mass-individualized products and services	Yitmen <i>et al.</i> (2023), Xu <i>et al.</i> (2021), Ikudayisi <i>et al.</i> (2023), Zizic <i>et al.</i> (2022), Leng <i>et al.</i> (2022), Gholami <i>et al.</i> (2021), Kusi-Sarpong <i>et al.</i> (2019), Bednar and Welch (2020), Venkatesh <i>et al.</i> (2020)
3.2	Balancing the three pillars (economy, environment, and society) in different stages to achieve success in construction	
3.3	Providing information to customers on social sustainability	
3.4	Traceability in multi-tier supply chains through blockchain technology	
3.5	Achieving Construction 5.0 with greater quantity, faster speed, better quality, and cost savings through sustainable practices	
4	<i>Opportunities for facilitating Construction 5.0</i>	
4.1	Implementing advancements in technology	Maddikunta <i>et al.</i> (2022), Ikudayisi <i>et al.</i> (2023), Marinelli (2023), Leng <i>et al.</i> (2022), Yitmen <i>et al.</i> (2023), Huang <i>et al.</i> (2022), Kravets <i>et al.</i> (2021), Turner <i>et al.</i> (2022)
4.2	Stimulating Operator 5.0	
4.3	Motivating Society 5.0	
4.4	Adopting circular economy	
4.5	Implementing sustainable building practices	
4.6	Enforcing resilience and adaptability	
4.7	Incorporating Smart Building Features	
5	<i>Challenges in facilitating Construction 5.0</i>	
5.1	Facing high initial costs and funding	Maddikunta <i>et al.</i> (2022), Xu <i>et al.</i> (2021), Fukuda (2020), Mukherjee <i>et al.</i> (2023), Breque <i>et al.</i> (2021), Demir <i>et al.</i> (2019), Porambage <i>et al.</i> (2021), Liyanage <i>et al.</i> (2020), Sharma <i>et al.</i> (2022), Stahl (2021)
5.2	Necessity of skilled workforce	
5.3	Maintaining data security and privacy	
5.4	Establishing regulatory and policy frameworks	
5.5	Managing scalability	
5.6	Imposing acceptance and adaptability	
5.7	Dealing with ethical Concerns	
		(continued)

Table 1. Continued

No	Constructs and indicators	References
6	<i>Implementing Smart, Sustainable and Resilient Buildings</i>	
6.1	<i>Smart Buildings</i>	
6.1.1	Energy efficiency	Roostaie and Nawari (2022), Almusaed and Yitmen (2023), Hao <i>et al.</i> (2023), Majdi <i>et al.</i> (2022), Ullah (2022), Al-Kodmany (2022), Almusaed <i>et al.</i> (2023), Li <i>et al.</i> (2022), Du <i>et al.</i> (2023)
6.1.2	Automation and control	
6.1.3	Occupant comfort	
6.1.4	Technology integration	
6.1.5	Data utilization	
6.1.6	Security and safety	
6.2	<i>Sustainable Buildings</i>	
6.2.1	Energy performance	
6.2.2	Water efficiency	
6.2.3	Materials and resources	
6.2.4	Indoor environmental quality	
6.2.5	Site selection and land Use	
6.2.6	Transportation and access	
6.3	<i>Resilient Buildings</i>	
6.3.1	Disaster preparedness	
6.3.2	Adaptive design	
6.3.3	Backup systems	
6.3.4	Climate resilience	
6.3.5	Structural integrity	
6.6.6	Community engagement	

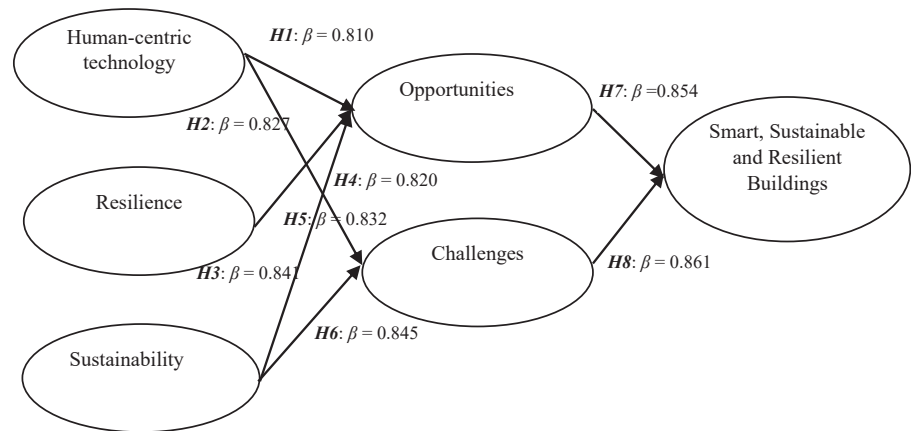
Source(s): Table created by authors**Source(s):** Figure created by authors**Figure 1.** Research methodology

context of each construction project. The selection process for these items was rigorous, ensuring they reflect the most significant and commonly discussed themes in the current literature.

The choice of opportunities and challenges as mediators in this model is grounded in theoretical and practical considerations. Opportunities represent the potential for innovation and advancement within the AEC industry, while challenges denote the barriers that must be addressed to realize these innovations. Drawing from [Author C]’s framework, it is argued that these mediators are essential in bridging theoretical constructs like human-centric technology, resilience, and sustainability with tangible outcomes in Construction 5.0. The literature suggests that without addressing these mediators, the direct impact of the independent variables on smart, sustainable, and resilient buildings would remain theoretical and detached from practical application. By considering both opportunities and challenges, stakeholders in the construction industry can better navigate the complexities of Construction 5.0, ensuring a balanced and sustainable approach to its development.

Figure 2 depicts the relationships between the six main aspects of this study: Human-centric technology for Construction 5.0, Resilience for Construction 5.0, Sustainability for Construction 5.0, Opportunities for facilitating Construction 5.0, and Challenges in facilitating Construction 5.0. The following hypotheses are developed to explain the relationships between the measured constructs and other variables based on Table 1’s theoretical foundations. The following ideas are derived from this analysis.

- H1. Adopting Human-centric technology in the AEC industry creates opportunities for facilitating Construction 5.0 in implementation of Smart, Sustainable and Resilient Buildings.
- H2. Sustaining Resilience in the AEC industry creates opportunities for facilitating Construction 5.0 in in implementation of Smart, Sustainable and Resilient Buildings.
- H3. Maintaining Sustainability in the AEC industry creates opportunities for facilitating Construction 5.0 in Smart, Sustainable and Resilient Buildings.
- H4. Adopting Human-centric technology in the AEC industry faces challenges for facilitating Construction 5.0 in implementation of Smart, Sustainable and Resilient Buildings.



Source(s): Figure created by authors

Figure 2. Hypothesized SEM model

- H5. Sustaining Resilience in the AEC industry faces challenges for facilitating Construction 5.0 in implementation of Smart, Sustainable and Resilient Buildings.
- H6. Maintaining Sustainability in the AEC industry faces challenges for facilitating Construction 5.0 in implementation of Smart, Sustainable and Resilient Buildings.
- H7. Seizing the opportunities for facilitating Construction 5.0 stimulates the implementation of Smart, Sustainable and Resilient Buildings.
- H8. Overcoming the challenges for facilitating Construction 5.0 endorses the implementation of Smart, Sustainable and Resilient Buildings.

3.2 Sampling and data collection

3.2.1 Questionnaire survey. The research adopted a positivist epistemological stance and specifically employed a quantitative research methodology to effectively address the research objectives, which aimed to assess the levels of relationships among the variables under investigation. To facilitate a more extensive exchange of information and enhance the researcher-respondent interaction, a computerized self-administered questionnaire (CSAQ) survey was employed. Given the variations in experiences among individuals working in different geographical locations, the study aimed to gather perspectives from practitioners operating in various developed countries. To facilitate data collection, the study surveyed professionals in Scandinavia, Europe, and North America who work in building construction, architectural design, engineering design, IT in construction, digital strategy consulting, and academia.

The research objectives were disseminated to 195 global organizations via various communication channels, including professional networking sites, email, and social media. A Likert scale accompanied each goal, and respondents were asked to rate their level of agreement on a scale ranging from 1 (strongly disagree) to 5 (strongly concur). Senior-level executives were selected as the primary contacts for survey queries within organizations, expecting their extensive experience to yield accurate results. The study collected responses from 138 participants, including 28 construction managers, 34 design managers, 29 BIM Coordinators, 25 digitalization consultants, and 22 academicians, each representing a single company. Distribution of respondents according to company type, role, size, and region is presented in [Table 2](#).

[Appendix](#) reveals that the questionnaire contained 47 questions on Opportunities and Challenges for Implementing Construction 5.0 for Smart, Sustainable, and Resilient Buildings. In providing a more comprehensive insight into the methodology employed in this study, a meticulous and rigorous approach was applied to ensure the robustness of the findings. The primary data collection tool utilized was CSAQ, strategically targeting architecture and engineering firms. The survey design was carefully crafted, incorporating questions that delve into nuanced aspects of Construction 5.0, human-centric technology, resilience, and sustainability within the AEC sector. The selection criteria for participants were methodically defined, considering expertise and experiences relevant to the subject matter.

3.2.2 Thematic analysis. Thematic analysis is a foundational method for qualitative research to uncover meaningful patterns and themes, providing a deeper understanding of the research topic. In this study, the interview responses were examined using a thematic approach, employing qualitative data analysis by Grounded theory coding. An iterative method transformed chaotic data into a map of the most relevant themes. [Table 3](#) provides details about the interviewees and the interviews themselves. Preliminary codes were assigned to describe the content. These codes were then used to search for themes within the interviews. The identified themes were subsequently examined, defined, and titled. The themes identified in the interviews regarding are as follows:

Table 2. Distribution of respondents according to company type, role, size, and region

Company type	Construction manager: 20%	Design manager: 25%	BIM coordinators: 21%	Digitalization consultants: 18%	Academic: 16%
Role	BIM: 15% Digital twin: 5%	BIM: 18% Digital twin: 7%	BIM: 15% Digital twin: 6%	Digital twin: 4% Digitalization: 6% BIM: 6% Software development: 2%	Ph.D. student: 16%
<i>Company size</i>					
Small (27%)	7%	7%	6%	4%	3%
Medium (39%)	11%	10%	8%	6%	4%
Large (34%)	8%	8%	7%	6%	5%
<i>Operating region</i>					
Scandinavia (36%)	9%	9%	8%	6%	4%
Europe (40%)	11%	9%	10%	6%	4%
N. America (24%)	7%	6%	5%	3%	3%

Source(s): Table created by authors

Table 3. Profiles of Interviewees and interview details

ID	Position (role)	Type of organization	Company size*	Operating region	Years of experience	Duration**
1	Digitalization Specialist	IT firm	Medium	Stockholm	15	55
2	BIM Manager	Design firm	Large	California, USA	10	50
3	BIM Manager	Project Management firm	Large	California, USA	25	50
4	Project Manager	Project Management Firm	Large	Dubai, UAE	20	55
5	Construction Manager	Contracting firm	Medium	Gothenburg	10	60
6	Digitalization Specialist	IT firm	Large	Gothenburg	10	60
7	BIM Coordinator	Design Firm	Medium	London, UK	15	55
8	BIM Specialist	Design firm	Large	Stockholm	20	55
9	BIM Manager	Contracting firm	Medium	Stockholm	25	60
10	Construction Manager	Contracting firm	Large	Stockholm	15	55
11	Project Manager	Project Management Firm	Large	London, UK	25	60
12	BIM Specialist	Design firm	Large	Dubai, UAE	10	55

Note(s): *Medium: 50–250 employees, Large: 250+ employees. **Interview duration in minutes
Source(s): Table created by authors

- (1) Human-Centric Automation and Integration in Construction 5.0
- (2) Resilient and Adaptive Industrial Systems for Construction 5.0
- (3) Sustainable and Integrated Practices for Construction 5.0
- (4) Opportunities for enabling Construction 5.0 through Technology, Sustainability, and Human-Centric Approaches

- (5) Overcoming Challenges in implementing Construction 5.0 through Technology, Sustainability, and Human-Centric Approaches
- (6) Integrated Sustainability and Resilience in Smart Building Design and Operations

3.3 Measurement of the SEM model

Multiple items were utilized to construct the method for evaluating the variables, increasing confidence in its precision and consistency. Each item was assessed using a five-point Likert scale, and everything was based on perception. Table 4 details the elements utilized to measure each variable. All factors exhibited loadings within the range of 0.70–0.90, and Cronbach's alpha values for all aspects were more significant than 0.70, indicating adequate reliability.

4. Findings and analysis of results

The intended model depicted in Figure 2 was tested using the statistical software package LISREL 11. Initial calculations included descriptive statistics and Pearson correlation coefficients. The structural equation model (SEM) was subsequently examined. SEM is a statistical method that employs a hypothesis-testing strategy to evaluate the relationship between a structural theory and a particular phenomenon. It facilitates comprehension of the actual world by bridging the gap between theoretical and empirical knowledge. Fundamental SEM stages include defining a theory-based model, establishing measurement methods for constructs, collecting data, and undertaking an analysis that includes statistics on the overall model fit and parameter estimates. This analysis reveals the causal relationships between concealed and visible variables. The model describes how hidden variables or theoretical constructs are influenced by observable variables or manifested through them. To assess the construct model's validity, along with the adequacy of assumed causal relationships in comparison to actual data, several indices were used, such as the Goodness-of-Fit Index (GFI), Adjusted Good-ness-of-Fit Index (AGFI), Comparative Fit Index (CFI), Normed Fit Index (NFI), Non-Normed Fit Index (NNFI), Root-Mean-Square Error of Approximation (RMSEA), and the ratio of "Chi-square" to the "Degree of Freedom" (χ^2/df). These goodness-of-fit indices determine whether the presumed model corresponds with empirical data and are significant indicators of the model's credibility and dependability. The outcomes of the proposed model, as illustrated in Figure 2, portray standardized structural coefficients that signify the relative significance of the variables' effects.

It is important to reiterate that every step of the SEM analysis was conducted with rigor and adherence to best practices in the field. Despite the perceived ambiguities, the SEM approach was meticulously designed to ensure that the relationships identified are both statistically significant and theoretically grounded. The model's fit indices, including GFI, AGFI, and RMSEA, all fall within acceptable ranges, providing confidence in the validity of the findings. However, we acknowledge the potential for alternative interpretations and the need for further empirical validation through additional studies, possibly including longitudinal data or alternative modeling approaches.

4.1 Descriptive statistics and correlation analysis

Table 4 displays the Means, Standard deviations, Factor loadings, Cronbach α , and Standardized Structural Coefficients of the variables. Table 5 shows the correlation matrix between factors to evaluate the significance of the relationships. Analyses of Pearson correlation confirmed the relationships between the independent and dependent variables investigated in this study. Each construct focuses on "Human-centric technology for Construction 5.0", "Resilience for Construction 5.0", "Sustainability for Construction 5.0", "Opportunities for facilitating Construction 5.0", and "Challenges for facilitating Construction 5.0". A p -value can indicate the importance of a connection. A p -value of less than 0.05 signifies a significant relationship between the two sets of evaluations. Analysis of

Table 4. Measurement model evaluation

Scale items	Item	Mean	SD	Loadings	Cronbach α	Parameter	Standardized structural coefficient
<i>Human-centric technology for Construction 5.0</i>	HCT					λ	
Machines and robots not replacing humans in the industry	HCT1	3.825	0.754	0.772		λ_1	0.751
Necessity of human involvement for achieving automation and digitization	HCT2	3.874	0.776	0.792		λ_2	0.773
Prioritization of human needs and interests as the foundation of the production process	HCT3	3.844	0.763	0.786	0.742	λ_3	0.764
Demand of intelligent robots understanding the interconnected relationships between humans and machines in unstructured environments	HCT4	3.873	0.775	0.797		λ_4	0.752
Autonomously ensuring the security and stability of communication networks that serve as social infrastructure	HCT5	3.866	0.771	0.793		λ_5	0.774
<i>Resilience for Construction 5.0</i>	RES					γ	
Re-thinking existing working methods and approaches	RES1	3.748	0.722	0.745		γ_1	0.722
Reducing the vulnerability of supply chains	RES2	3.781	0.742	0.761		γ_2	0.741
Focusing on the ability of firms to cope with external uncertainties	RES3	3.741	0.734	0.758	0.720	γ_3	0.731
Focusing on the resilience of a wider range of industrial systems	RES4	3.826	0.753	0.771		γ_4	0.748
Technology systems and solutions prioritizing stability over resilience and providing more prevalent and mass-automation solutions	RES5	3.842	0.762	0.786		γ_5	0.762
<i>Sustainability for Construction 5.0</i>	SUS					θ	
Implementing the sustainable construction vision regarding the decentralized connection of socialized production resources and products to deliver mass-individualized products and services	SUS1	03.841	0.762	0.784		θ_1	0.760
Balancing the three pillars (economy, environment, and society) in different stages to achieve success in construction	SUS2	3.874	0.776	0.795		θ_2	0.776
Providing information to customers on social sustainability	SUS3	3.826	0.753	0.773	0.740	θ_3	0.749

(continued)

Table 4. Continued

Scale items	Item	Mean	SD	Loadings	Cronbach α	Parameter	Standardized structural coefficient
Traceability in multi-tier supply chains through blockchain technology	SUS4	3.824	0.751	0.776		θ_4	0.742
Achieving Construction 5.0 with greater quantity, faster speed, better quality, and cost savings through sustainable practices	SUS5	3.866	0.771	0.799		θ_5	0.778
<i>Opportunities for facilitating Construction 5.0</i>	OPP						
Implementing advancements in technology	OPP1	4.125	0.811	0.825		ω_1	0.804
Stimulating Operator 5.0	OPP2	4.236	0.822	0.847		ω_2	0.823
Motivating Society 5.0	OPP3	4.347	0.826	0.869		ω_3	0.845
Adopting circular economy	OPP4	4.028	0.806	0.806	0.863	ω_4	0.786
Implementing sustainable building practices	OPP5	4.454	0.838	0.891		ω_5	0.872
Enforcing resilience and adaptability	OPP6	4.502	0.845	0.900		ω_6	0.883
Incorporating smart building features	OPP7	4.526	0.859	0.903		ω_7	0.886
<i>Challenges in facilitating Construction 5.0</i>	CHA					μ	
Facing high initial costs and funding	CHA1	4.251	0.829	0.850		μ_1	0.831
Necessity of skilled workforce	CHA2	4.367	0.832	0.873		μ_2	0.852
Maintaining data security and privacy	CHA3	4.321	0.819	0.864		μ_3	0.843
Establishing regulatory and policy frameworks	CHA4	4.458	0.841	0.892	0.882	μ_4	0.874
Managing scalability	CHA5	4.465	0.843	0.893		μ_5	0.873
Imposing acceptance and adaptability	CHA6	4.503	0.848	0.901		μ_6	0.884
Dealing with ethical concerns	CHA7	4.514	0.851	0.905		μ_7	0.885
<i>Implementing smart, sustainable, and resilient buildings</i>	SSR						
<i>Smart buildings</i>							
Energy efficiency	SSR1	4.522	0.852	0.904		δ_1	0.885
Automation and control	SSR2	4.534	0.858	0.907		δ_2	0.888
Occupant comfort	SSR3	4.516	0.850	0.903		δ_3	0.884
Technology integration	SSR4	4.502	0.847	0.900	0.903	δ_4	0.883
Data utilization	SSR5	4.511	0.849	0.902		δ_5	0.882
Security and safety	SSR6	4.507	0.848	0.901		δ_6	0.881
<i>Sustainable buildings</i>							
Energy performance	SSR7	4.623	0.867	0.925		δ_7	0.897
Water efficiency	SSR8	4.509	0.849	0.902		δ_8	0.882
Materials and resources	SSR9	4.537	0.858	0.907		δ_9	0.888
Indoor environmental quality	SSR10	4.541	0.860	0.908	0.906	δ_{10}	0.889
Site selection and land Use	SSR11	4.482	0.844	0.896		δ_{11}	0.878
Transportation and access	SSR12	4.491	0.845	0.898		δ_{12}	0.890

(continued)

Table 4. Continued

Scale items	Item	Mean	SD	Loadings	Cronbach α	Parameter	Standardized structural coefficient
<i>Resilient buildings</i>							
Disaster preparedness	SSR13	4.552	0.862	0.910	0.917	δ_{13}	0.892
Adaptive design	SSR14	4.618	0.866	0.924		δ_{14}	0.896
Backup systems	SSR15	4.503	0.847	0.900		δ_{15}	0.883
Climate resilience	SSR16	4.634	0.869	0.927		δ_{16}	0.899
Structural integrity	SSR17	4.628	0.867	0.926		δ_{17}	0.898
Community engagement	SSR18	4.584	0.863	0.917		δ_{18}	0.895
Source(s): Table created by authors							

the correlation matrix reveals notable and favorable linear connections among factors representing the variables “Human-centric technology for Construction 5.0”, “Resilience for Construction 5.0”, “Sustainability for Construction 5.0”, “Opportunities for facilitating Construction 5.0”, “Challenges in facilitating Construction 5.0” and “Implementing Smart, Sustainable and Resilient Buildings.” The correlation between the constructs “Implementing Smart, Sustainable, and Resilient Buildings” and “Opportunities for facilitating Construction 5.0”, and “Implementing Smart, Sustainable, and Resilient Buildings and “Challenges for facilitating Construction 5.0” have the highest values of 0.826 and 0.835 respectively.

While these correlations are strong, it is crucial to consider the potential limitations of the methodology that could affect the interpretation of these results. The relationships identified are based on the specific constructs defined within the SEM framework, and any variations in the underlying assumptions could lead to different outcomes. Therefore, these results should be viewed as part of a broader conversation about Construction 5.0, with recognition that further research is needed to confirm and expand upon these findings.

4.2 Confirmatory factor analysis and reliability

One of SEM’s primary advantages is its ability to combine Confirmatory factor analysis (CFA) and path analysis, enabling the assessment of latent constructs through several observed variables. SEM often incorporates CFA to validate or confirm the measurement model within the larger structural equation model. CFA allows researchers to test whether the observed variables adequately represent the underlying latent constructs as hypothesized in the theoretical model. CFA identified the primary dimensions within the Human-centric technology, Resilience, Sustainability, Opportunities, and Challenges in facilitating Construction 5.0 and Implementing Smart, Sustainable, and Resilient Buildings constructs. The variables within these constructs were subjected to empirical testing and validation through principal component analysis. A summary of the outcomes can be found in Table 4. Computing indices of overall and individual sampling adequacy assessed the appropriateness of the data for factor analysis. Values above the threshold of 0.5 are deemed acceptable or satisfactory. Cronbach’s alphas were used to evaluate the internal consistency and estimate the dependability of the derived components. Cronbach’s alpha (α) is calculated based on the mean correlation across variables inside a factor, and a minimal threshold of 0.7 is considered acceptable. The Cronbach’s alpha values were assessed to evaluate the reliability coefficients (α) for the constructs mentioned in Table 4. It was found that all the reliability coefficients demonstrated satisfactory levels of dependability. Certain constructs exhibited more excellent dependability compared to others. The constructs “Opportunities for facilitating Construction 5.0”, “Challenges in facilitating Construction 5.0”, and “Implementing Smart, Sustainable and Resilient Buildings” have the highest reliability coefficients α with values of 0.917, 0.906,

Table 5. Pearson correlation analysis

Latent construct	Human-centric technology for construction 5.0	Resilience for construction 5.0	Sustainability for construction 5.0	Opportunities for facilitating construction 5.0	Challenges in facilitating construction 5.0	Implementing smart, sustainable, and resilient buildings
Human-centric technology for Construction 5.0	1.000					
Resilience for Construction 5.0	0.654**	1.000				
Sustainability for Construction 5.0	0.692**	0.714**	1.000			
Opportunities for facilitating Construction 5.0	0.729**	0.745**	0.776**	1.000		
Challenges in facilitating Construction 5.0	0.786**	0.763**	0.785**	0.797**	1.000	
Implementing smart, sustainable, and resilient buildings	0.791***	0.796***	0.818***	0.826***	0.835***	1.000
Note(s): ρ = level of significance ** $\rho < 0.05$, *** $\rho < 0.01$, $n = 138$						
Source(s): Table created by authors						

0.903, 0.882, and 0.863 respectively. The variables “Climate resilience”, “Energy performance,” “Automation and control”, “Dealing with ethical concerns”, and “Incorporating Smart Building Features” have the highest factor loading with values of 0.927, 0.925, 0.907, 0.905, and 0.903, respectively.

The CFA results provide further support for the validity of the constructs used in this study. Despite the methodological concerns, the high factor loadings and Cronbach’s alpha values indicate that the constructs are reliably measured. However, it is important to continue refining these constructs and testing them in different contexts to ensure that the results are generalizable across various scenarios within the AEC industry.

4.3 Thematic analysis

A comprehensive thematic analysis of the interviewees’ captured ideas led to the identification of six major themes. These themes address key issues such as Human-Centric Automation and Integration in Construction 5.0, Resilient and Adaptive Industrial Systems for Construction 5.0, Sustainable and Integrated Practices for Construction 5.0, Opportunities for Enabling Construction 5.0 through Technology, Sustainability, and Human-Centric Approaches, Overcoming Challenges in Implementing Construction 5.0 through Technology, Sustainability, and Human-Centric Approaches, and Integrated Sustainability and Resilience in Smart Building Design and Operations. Table 6 summarizes these themes, providing a brief description of the core ideas, challenges, and opportunities highlighted during the interviews.

While the thematic analysis provides valuable qualitative insights, we acknowledge that the interpretation of these themes is subject to the researcher’s perspective and the specific context of the interviews. To strengthen the reliability of these findings, future studies could benefit from triangulating these results with additional data sources or involving multiple researchers in the coding process to reduce potential bias.

4.4 SEM analysis

The utilization and validation of structural equation modeling (SEM) are prevalent in diverse scientific disciplines due to their capacity to infer relationships between unobservable variables based on observable ones. Compared to other multivariate data analysis approaches, structural equation modeling (SEM) exhibits three significant properties (Xiong *et al.*, 2015). (1) The proposed method can estimate numerous and linked dependency connections. (2) The proposed method can represent unobservable notions inside these relationships and correct measurement errors throughout estimating. (3) The proposed method can create a model that comprehensively understands the entire collection of relationships. The diagram shown in Figure 2 depicts the theoretical frameworks that provide the basis for the connections between the variables that are considered independent and dependent. This conceptual framework describes the postulated interconnections among Human-centric technology for Construction 5.0, Resilience for Construction 5.0, Sustainability for Construction 5.0, Opportunities for facilitating Construction 5.0, and Challenges in facilitating Construction 5.0, in the context of implementing Smart, Sustainable and Resilient Buildings. A sample size of 138 was used to evaluate the predicted correlations.

The adoption of the SEM method was intentional, chosen for its efficacy in evaluating complex relationships within our research model. SEM facilitated a nuanced analysis, allowing for a quantitative exploration of the opportunities and challenges associated with the implementation of Construction 5.0 for smart, sustainable, and resilient buildings. By elaborating on these methodological details, this study aims to provide a transparent and comprehensive account, offering readers a deeper insight into the scientific rigor underpinning the research.

Statistical assessments were employed to gauge the model’s adequacy, and it was found that the hypothesized model fit well, as evidenced by a significant Chi-square statistic ($\chi^2 = 169.24$

Table 6. Coded themes from interviews

Theme	Description
Human-centric automation and integration in Construction 5.0	This theme focuses on the harmonious integration of human involvement and advanced robotics in the construction industry, emphasizing the necessity of human-centric approaches for achieving successful automation and digitization. It underscores the importance of prioritizing human needs and interests as the foundation of the production process, while leveraging intelligent robots that understand the interconnected relationships between humans and machines in unstructured environments
Resilient and adaptive industrial systems for Construction 5.0	This theme encompasses the need to innovate and adapt existing working methods and approaches to enhance the resilience and adaptability of industrial systems. It emphasizes reducing the vulnerability of supply chains and increasing the ability of firms to cope with external uncertainties. The focus extends to ensuring the resilience of a broader range of industrial systems by prioritizing stability in technology systems and solutions while integrating mass-automation to streamline processes
Sustainable and integrated practices for Construction 5.0	This theme focuses on implementing a vision for sustainable construction that integrates decentralized socialized production resources and products to deliver mass-individualized products and services. It emphasizes balancing the economic, environmental, and social pillars throughout different stages of construction to achieve overall success. The theme also highlights the importance of providing information on social sustainability to customers and ensuring traceability in multi-tier supply chains through blockchain technology. The goal is to achieve Construction 5.0 with greater efficiency, better quality, and cost savings through sustainable practices
Opportunities for enabling Construction 5.0 through technology, sustainability, and human-centric approaches	This theme focuses on the holistic advancement of construction by integrating cutting-edge technologies, stimulating human-centric approaches like Operator 5.0 and Society 5.0, and adopting sustainable and resilient building practices. It emphasizes the importance of the circular economy and smart building features to create a sustainable, adaptive, and efficient construction environment
Overcoming challenges in implementing Construction 5.0 through technology, sustainability, and human-centric approaches	This theme addresses the multifaceted challenges associated with the implementation of advanced technologies in the construction industry. It encompasses the financial, regulatory, ethical, and practical hurdles that must be navigated to ensure successful adoption and integration of new technological solutions. It highlights the adoption of circular economy principles, the implementation of resilient and adaptable building designs, and the incorporation of smart building features to create efficient, sustainable, and adaptive construction environments

(continued)

Table 6. Continued

Theme	Description
Integrated sustainability and resilience in smart building design and operations	This theme encompasses the holistic approach to sustainable and resilient building design and operations. It integrates various factors that contribute to energy efficiency, occupant comfort, technology integration, data utilization, security, safety, and resilience. By integrating these factors into building design and operations, stakeholders can create environments that are environmentally responsible, resource-efficient, safe, and resilient to climate impacts and emergencies

Source(s): Table created by authors

with $df = 92$; $p < 0.01$). The utilization of SEM techniques facilitated the execution of path analyses, aiding in examining relationships between the model constructs (hypotheses) and assessing the model's goodness of fit. The outcomes demonstrated that all standardized loadings for the respective constructs exceeded 0.5 ($p < 0.001$). The overall adequacy of the model was statistically significant ($\chi^2 = 169.24$ with $df = 92$; $p < 0.01$). The goodness-of-fit statistics yielded the following results: comparative fit index (CFI) = 0.934, goodness-of-fit index (GFI) = 0.920, adjusted goodness-of-fit index (AGFI) = 0.915, normed fit index (NFI) = 0.928, non-normed fit index (NNFI) = 0.924, and root-mean-square error of approximation (RMSEA) = 0.066. Different software packages were employed because if the majority of indices indicate a satisfactory fit, then such a fit is likely to be present. The outcomes of GFI, AGFI, CFI, NFI, and NNFI all surpassed the threshold of 0.90, signifying a solid fit for the hypothesized model. A ratio of model fit statistics to degrees of freedom below 3 indicates an appropriate model fit ($\chi^2/df = 1.840$). Hence, it can be categorized that the hypothesized model in Figure 2 closely aligns with the data. The results of goodness-of-fit measures for the hypothesized model are detailed in Table 7, all of which strongly suggest a highly suitable fit for the proposed model.

4.5 Hypothesis test

To evaluate Hypotheses 1–8, the proposed model was examined through LISREL 11, which estimated the connections between Human-centric technology and Opportunities for enabling Construction 5.0 (H1), Resilience and Opportunities for facilitating Construction 5.0 (H2), Sustainability and Opportunities for facilitating Construction 5.0 (H3), Human-centric

Table 7. Overall goodness-of fit measures for the hypothesized model

Statistics	Fitness criteria	Values	Fitness judgment
χ^2	$p < 0.01$	169.24	$p < 0.000 < 0.01$ Yes
RMSEA	<0.08 (is excellent, and <0.08 is good)	0.066	Yes (good)
GFI	>0.90	0.920	Yes
AGFI	>0.90	0.915	Yes
NFI	>0.90	0.928	Yes
NNFI	>0.90	0.924	Yes
CFI	>0.90	0.934	Yes
χ^2/df	<2.00	1.840	Yes

Source(s): Table created by authors

technology and Challenges for facilitating Construction 5.0 (H4), Resilience and Challenges for facilitating Construction 5.0 (H5), Sustainability and Challenges for facilitating Construction 5.0 (H6), Opportunities and Implementation of Smart, Sustainable and Resilient Buildings (H7), and Challenges and Implementation of Smart, Sustainable and Resilient Buildings (H8). The hypotheses concerning these relationships were validated using *t*-statistics. *t*-values greater than 1.65, 1.98, and 2.576 were deemed significant at the 0.10, 0.05 and 0.01 levels, respectively. Human-centric technology for Construction 5.0 significantly and positively influenced ($\rho < 0.05$) Opportunities for facilitating Construction 5.0 and Challenges for facilitating Construction 5.0 (with values of H1 = 0.810, *t*-value = 4.421; H4 = 0.820, *t*-value = 4.526). Resilience for Construction 5.0 significantly and positively influenced ($\rho < 0.05$) Opportunities for facilitating Construction 5.0 and Challenges for facilitating Construction 5.0 (with values of H2 = 0.827, *t*-value = 4.618; H5 = 0.832, *t*-value = 4.742). Sustainability for Construction 5.0 significantly and positively influenced ($\rho < 0.05$) Opportunities for facilitating Construction 5.0 and Challenges for facilitating Construction 5.0 (with values of H3 = 0.841, *t*-value = 5.012; H6 = 0.845, *t*-value = 5.274). Opportunities for facilitating Construction 5.0 significantly and positively influenced ($\rho < 0.01$) Implementing Smart, Sustainable, and Resilient Buildings (with value of H7 = 0.854, *t*-value = 5.325). Challenges for facilitating Construction 5.0 significantly and positively influenced ($\rho < 0.01$) Implementing Smart, Sustainable and Resilient Buildings (with value of H8 = 0.861, *t*-value = 5.481). Thus, these findings support hypotheses 1–8. Table 8 exhibits the results of the parameter estimates of the hypothesized model. Considering the standardized parameter estimates, the findings indicate that all eight presumed relationships are categorized as statistically significant. Challenges for facilitating Construction 5.0 – Implementation of Smart, Sustainable and Resilient The importance of buildings is notably high, as shown by a path coefficient of 0.861. This finding suggests that addressing the issues associated with enabling Construction 5.0 is closely linked to successfully adopting Smart, Sustainable, and Resilient Buildings. The significance of opportunities for facilitating Construction 5.0 about implementing Smart, Sustainable, and Resilient Buildings is ranked second highest, with a path coefficient of 0.854. This indicates that utilizing opportunities for facilitating Construction 5.0 positively influences the implementation of Smart, Sustainable, and

Table 8. Parameter estimates for structural equation model

Hypothesized model	Parameter coefficient	<i>t</i> -statistics	Acceptability
H1: Human-centric technology → Opportunities for facilitating Construction 5.0	$\beta = 0.810^{**}$	4.421	Accepted
H2: Resilience → Opportunities for facilitating Construction 5.0	$\beta = 0.827^{**}$	4.618	Accepted
H3: Sustainability → Opportunities for facilitating Construction 5.0	$\beta = 0.841^{**}$	5.012	Accepted
H4: Human-centric technology → Challenges for facilitating Construction 5.0	$\beta = 0.820^{**}$	4.526	Accepted
H5: Resilience → Challenges for facilitating Construction 5.0	$\beta = 0.832^{**}$	4.742	Accepted
H6: Sustainability → Challenges for facilitating Construction 5.0	$\beta = 0.845^{**}$	5.274	Accepted
H7: Opportunities → Implementation of Smart, Sustainable and Resilient Buildings	$\beta = 0.854^{***}$	5.325	Accepted
H8: Challenges → Implementation of Smart, Sustainable and Resilient Buildings	$\beta = 0.861^{***}$	5.481	Accepted

Note(s): ρ = level of significance, $^{**}\rho < 0.05$, and $^{***}\rho < 0.01$
Source(s): Table created by authors

Resilient Buildings. [Table 4](#) presents the standardized structural coefficients of the variables: Human-centric technology for Construction 5.0, Resilience for Construction 5.0, Sustainability for Construction 5.0, Opportunities for facilitating Construction 5.0, Challenges for facilitating Construction 5.0, Implementing Smart, Sustainable and Resilient Buildings. These coefficients indicate the degree of relative significance in the relationships between these variables. The variables Motivating Society 5.0, Implementing sustainable building practices, Enforcing resilience and adaptability, and Incorporating smart building features in terms of opportunities, and Managing scalability, Establishing regulatory and policy frameworks, Imposing acceptance and adaptability, and Dealing with ethical concerns in terms of challenges had the highest standardized structural coefficients with values 0.845, 0.872, 0.883, 0.886, and 0.873, 0.874, 0.884, 0.885 respectively validating the empirical modeling work.

[Hypothesis 1](#) proposes that integrating human-centric technology within the Architecture, Engineering, and Construction (AEC) business presents potential avenues for advancing the implementation of Construction 5.0, particularly in constructing intelligent, environmentally friendly, and adaptable buildings. [Hypothesis 2](#) suggests that maintaining resilience within the AEC sector presents chances for the advancement of Construction 5.0, namely in implementing intelligent, environmentally conscious, and robust structures. [Hypothesis 3](#) suggests that preserving sustainability within the Architecture, Engineering, and Construction (AEC) business presents potential avenues for advancing the implementation of Construction 5.0, specifically in constructing intelligent, environmentally friendly, and resilient buildings. [Figure 2](#) shows that path coefficients of 0.810, 0.827, and 0.841 were observed, indicating a positive association in the predicted model. These coefficients were found to be statistically significant.

[Hypothesis 4](#) suggests that the integration of human-centric technology in the Architecture, Engineering, and Construction (AEC) business encounters obstacles in promoting the realization of Construction 5.0, which aims to enable the development of intelligent, sustainable, and resilient structures. [Hypothesis 5](#) suggests that the AEC business needs help maintaining resilience while promoting the adoption of Construction 5.0, which involves the construction of intelligent, sustainable, and resilient buildings. [Hypothesis 6](#) suggests that the AEC industry needs help advertising the use of Construction 5.0, which aims to facilitate the development of intelligent, sustainable, and resilient buildings, hence hindering sustainability goals. The path coefficients of 0.820, 0.832, and 0.845, as seen in [Figure 2](#), indicate a statistically significant and positive connection in the predicted model.

[Hypothesis 7](#) suggests that using chances to enhance Construction 5.0 may promote the adoption of intelligent, environmentally friendly, and robust structures. [Hypothesis 8](#) proposes that addressing the obstacles associated with promoting Construction 5.0 supports the adoption of innovative, environmentally-friendly, and strong networks. The results shown in [Figure 2](#) demonstrate that the path coefficients of 0.854 and 0.861, representing the predicted model's connection, were both statistically significant and positive.

5. Discussion

5.1 Theoretical contributions

The discussion regarding the implications of the findings extends beyond the immediate benefits of integrating human-centric technology, resilience, sustainability, and addressing the challenges for Construction 5.0 in the AEC industry. An overarching theme emerges, emphasizing the interconnectedness of these factors in shaping the future of construction. As the industry moves towards a paradigm shift, it becomes evident that the successful realization of intelligent, sustainable, and resilient buildings is contingent upon a holistic approach that prioritizes human needs, environmental responsibility, and technological innovation. The challenges posed, such as high initial costs, funding hurdles, and the need for a skilled workforce, underscore the complexity of this transformative journey. Addressing these

challenges transparently and effectively becomes imperative, necessitating innovative financial models, comprehensive training programs, and ethical considerations. In navigating these multifaceted dynamics, the AEC industry has the unique opportunity not only to redefine construction practices but also to create a built environment that resonates deeply with the values and well-being of the communities it serves.

The results of the SEM indicate that 47 identified variables facilitating Construction 5.0 in implementation of Smart, Sustainable and Resilient Buildings were rigorously confirmed through CFA and hypothesis testing (parameter estimates, model fit, *t*-statistics).

The results of evaluating the cause-and-effect connections between human-centric technology in AEC industry and the opportunities for facilitating Construction 5.0 in implementation of smart, sustainable, and resilient buildings, as highlighted in [Hypothesis 1](#), align with prior research ([Xu et al., 2021](#); [Zizic et al., 2022](#); [Leng et al., 2022](#); [Mourtzis et al., 2022](#); [Yitmen et al., 2023](#); [Fonda and Meneghetti, 2022](#); [Nguyen Ngoc et al., 2022](#); [Wang et al., 2022](#); [Kadir and Broberg, 2021](#); [Colla et al., 2021](#); [He et al., 2017](#); [Huang et al., 2022](#); [Kravets et al., 2021](#); [Nahavandi, 2019](#); [Papetti et al., 2020](#); [Ivanov, 2023](#); [Romero and Stahre, 2021](#); [Kusi-Sarpong et al., 2019](#); [Kong et al., 2019](#); [How et al., 2020](#); [He et al., 2017](#); [Horvatic and Lipic, 2021](#); [Baicun and Yuan, 2022](#)). Integrating human-centric technology in the AEC industry advances Construction 5.0, fostering intelligent, sustainable, and resilient structures. This process emphasizes that machines and robots complement human knowledge rather than replace it, highlighting the need for human participation in automation and digitalization. This development focuses on human needs as the foundation for production, enhancing workforce capabilities. A key aspect is the need for advanced robotic systems that understand human-machine interactions in unstructured environments, ensuring communication network security and efficiency. This transition supports Operator 5.0, equipping the workforce with skills to use technology effectively, and promotes Society 5.0, advocating for sustainable practices and a circular economy. Smart building features improve energy efficiency, automation, comfort, and security. Sustainable practices include energy performance, water efficiency, and mindful resource use, creating an eco-friendly environment. Resilient buildings incorporate disaster preparedness, adaptive design, and community engagement, ensuring infrastructure can withstand challenges. This transformative journey enriches the industry and society by prioritizing human-technology harmony.

The results of evaluating the cause-and-effect connections between resilience in the AEC sector and the opportunities for facilitating Construction 5.0 in implementation of smart, sustainable, and resilient buildings, as highlighted in [Hypothesis 2](#), align with prior research conducted by various scholars ([Xu et al., 2021](#); [Zizic et al., 2022](#); [Leng et al., 2022](#); [Mourtzis et al., 2022](#); [Yitmen et al., 2023](#); [Romero and Stahre, 2021](#)). Maintaining resilience in the AEC industry strengthens its core and advances Construction 5.0, aiming for intelligent, sustainable, and resilient structures. This requires reevaluating current strategies to minimize supply chain vulnerabilities and enhance risk management. By embracing a broader spectrum of industrial systems, we prioritize stability and implement automated solutions for significant change. Technological advancements drive this evolution, fostering Operator 5.0—a workforce adept at navigating the digital landscape—and Society 5.0, committed to sustainable practices and circular economy principles. Resilient buildings, featuring disaster preparedness, adaptive design, backup systems, and climate resilience, ensure readiness for unforeseen challenges while maintaining structural integrity and community engagement. This transformation leads to a built environment that is intelligent, sustainable, resilient, and community-focused.

The results of evaluating the cause-and-effect connections between sustainability in the AEC industry and the opportunities for facilitating Construction 5.0 in implementation of smart, sustainable, and resilient buildings are highlighted in [Hypothesis 3](#), which is consistent with earlier research ([Xu et al., 2021](#); [Zizic et al., 2022](#); [Leng et al., 2022](#); [Yitmen et al., 2023](#); [Gholami et al., 2021](#); [Ivanov, 2023](#); [Romero and Stahre, 2021](#); [Kusi-Sarpong et al., 2019](#); [Bednar and Welch, 2020](#); [Venkatesh et al., 2020](#)). Preserving sustainability in the AEC

industry shows a commitment to environmental responsibility and promotes Construction 5.0, which focuses on intelligent, sustainable, and resilient structures. This vision involves adopting sustainable building techniques to create decentralized links between production resources and products, enabling large-scale customization of goods and services. Success in construction depends on balancing economic, environmental, and societal aspects throughout project phases. Blockchain technology can help communicate social sustainability and material traceability in supply chains. Achieving Construction 5.0 involves enhanced quantity, speed, quality, and cost reduction through sustainable practices. This progress relies on technological advancements and the rise of Operator 5.0—a skilled workforce navigating these changes. Society 5.0 shares a commitment to sustainability, incorporating circular economy principles and sustainable construction methods emphasizing energy efficiency, automation, occupant comfort, and data utilization. Sustainable buildings focus on energy performance, water efficiency, responsible materials, and interior quality. Integrating site selection, land use, and accessible transportation is crucial. The AEC industry aims for a future where intelligent, eco-friendly, and resilient buildings support community well-being.

The results of evaluating the cause-and-effect connections between human-centric technology in the AEC industry and the challenges for facilitating Construction 5.0 in implementation of smart, sustainable, and resilient buildings, as highlighted in [Hypothesis 4](#), are consistent with earlier research conducted by various scholars ([Maddikunta et al., 2022](#); [Xu et al., 2021](#); [Yitmen et al., 2023](#); [Fukuda, 2020](#); [Mukherjee et al., 2023](#); [Breque et al., 2021](#); [Demir et al., 2019](#); [Liyanage et al., 2020](#); [Sharma et al., 2022](#); [Stahl, 2021](#); [Vesnic-Alujevic et al., 2020](#); [Nahavandi, 2019](#); [Lu et al., 2021](#); [Papetti et al., 2020](#); [Lu et al., 2022](#)). Integrating human-centric technology in the AEC industry is key to advancing Construction 5.0 and creating intelligent, sustainable, and resilient structures. This paradigm emphasizes that machines and robots enhance rather than replace human labor, with human participation crucial for effective automation and digitalization. Intelligent robots are needed to understand the complex dynamics between people and machines, particularly in maintaining secure communication networks, vital for social infrastructure. Challenges include high initial costs, the need for innovative financial models, a skilled workforce, data security, and balancing regulatory frameworks. Ensuring ethical impacts on employment and decision-making is also critical. Smart building features like energy efficiency, automation, occupant comfort, and technology integration are essential. The AEC industry has the transformative opportunity to create intelligent, sustainable, and resilient structures aligned with human needs and values.

The findings of assessing the causal relationships between resilience in the AEC industry and challenges for facilitating Construction 5.0 in implementation of Smart, Sustainable and Resilient Buildings emphasized in [Hypothesis 5](#) align with the previous studies ([Maddikunta et al., 2022](#); [Ikudayisi et al., 2023](#); [Zizic et al., 2022](#); [Mourtzis et al., 2022](#); [Yitmen et al., 2023](#); [Fukuda, 2020](#); [Mukherjee et al., 2023](#); [Breque et al., 2021](#); [Demir et al., 2019](#); [Liyanage et al., 2020](#); [Sharma et al., 2022](#); [Stahl, 2021](#); [Vesnic-Alujevic et al., 2020](#); [Ivanov, 2023](#); [Romero and Stahre, 2021](#)). Sustaining resilience in the AEC industry is vital for advancing Construction 5.0 and achieving smart, sustainable, and resilient buildings. This requires rethinking existing methods to reduce supply chain vulnerabilities and enhance firms' abilities to manage uncertainties. Resilience should encompass a broad range of industrial systems, with technology prioritizing stability and mass automation. However, challenges include high initial costs, funding, and the need for a skilled workforce adept at navigating Construction 5.0. Ensuring data security and privacy, establishing regulatory frameworks, managing scalability, and fostering stakeholder acceptance and adaptability are crucial. Ethical concerns about the impact of automation and AI on employment and decision-making must be addressed transparently. A comprehensive approach to building smart, sustainable, and resilient structures involves enhancing energy efficiency, automation, occupant comfort, and technology integration. Resilient buildings must feature disaster preparedness, adaptable design, backup systems, climate resilience, structural integrity, and community engagement.

The AEC industry can redefine construction, creating a built environment aligned with community well-being and values.

The findings of assessing the causal relationships between sustainability in the AEC industry and challenges for facilitating Construction 5.0 in implementation of smart, sustainable and resilient buildings emphasized in [Hypothesis 6](#) align with the previous studies ([Xu et al., 2021](#); [Ikudayisi et al., 2023](#); [Zizic et al., 2022](#); [Leng et al., 2022](#); [Yitmen et al., 2023](#); [Gholami et al., 2021](#); [Kusi-Sarpong et al., 2019](#); [Bednar and Welch, 2020](#); [Venkatesh et al., 2020](#)). Maintaining sustainability in the AEC industry is crucial for advancing Construction 5.0 and realizing smart, sustainable, and resilient buildings. This involves implementing a vision of decentralized connections among production resources to deliver individualized products and services. Success hinges on balancing economic, environmental, and societal pillars, and providing customers with information on social sustainability and supply chain traceability, facilitated by blockchain technology. Achieving Construction 5.0, with its goals of greater quantity, faster speed, better quality, and cost savings, is closely tied to sustainable practices but faces challenges like high initial costs and funding needs. A skilled workforce, data security, and regulatory frameworks are essential. Managing scalability, stakeholder acceptance, and ethical concerns about automation and AI impacts are critical. Smart building approaches focus on energy efficiency, automation, occupant comfort, and technology integration.

The findings of assessing the causal relationships between opportunities for facilitating Construction 5.0 in implementation of smart, sustainable and resilient buildings emphasized in [Hypothesis 7](#) align with the previous studies ([Maddikunta et al., 2022](#); [Ikudayisi et al., 2023](#); [Marinelli, 2023](#); [Leng et al., 2022](#); [Yitmen et al., 2023](#); [Huang et al., 2022](#); [Kravets et al., 2021](#); [Turner et al., 2022](#); [Roostaie and Nawari, 2022](#); [Almusaed and Yitmen, 2023](#); [Hao et al., 2023](#); [Majdi et al., 2022](#); [Ullah, 2022](#); [Al-Kodmany, 2022](#); [Almusaed et al., 2023](#); [Li et al., 2022](#); [Du et al., 2023](#)). Seizing opportunities presented by Construction 5.0 is key to implementing smart, sustainable, and resilient buildings. This transformation relies on technological advancements, enhancing infrastructure and fostering Operator 5.0—a workforce adept at navigating the digital era. Society 5.0 promotes sustainability, including circular economy principles and sustainable building practices. Smart buildings focus on optimizing energy efficiency, automation, occupant comfort, technology integration, and data utilization while ensuring robust security and safety. Sustainable buildings feature superior energy performance, increased water efficiency, responsible resource use, improved indoor environmental quality, and thoughtful site selection and land use, complemented by accessible transportation solutions. Resilient buildings, with disaster preparedness, adaptive design, backup systems, climate resilience, structural integrity, and community engagement, prepare us for unforeseen challenges. Embracing this approach, the AEC industry can redefine construction, aligning it with community well-being and values.

The findings of assessing the causal relationships between challenges for facilitating Construction 5.0 in implementation of smart, sustainable and resilient buildings emphasized in [Hypothesis 8](#) align with the previous studies ([Maddikunta et al., 2022](#); [Xu et al., 2021](#); [Fukuda, 2020](#); [Mukherjee et al., 2023](#); [Breque et al., 2021](#); [Demir et al., 2019](#); [Porambage et al., 2021](#); [Liyanage et al., 2020](#); [Sharma et al., 2022](#); [Stahl, 2021](#); [Vesnic-Alujevic et al., 2020](#); [Hao et al., 2023](#); [Majdi et al., 2022](#); [Ullah, 2022](#); [Al-Kodmany, 2022](#); [Almusaed et al., 2023](#); [Li et al., 2022](#); [Du et al., 2023](#)). Overcoming the challenges on the path to Construction 5.0 is essential for creating smart, sustainable, and resilient buildings. These challenges include high initial costs, securing funding, and the need for a skilled workforce. Maintaining data security and privacy is critical, alongside establishing regulatory frameworks that balance innovation and safety. Managing scalability and ensuring stakeholder acceptance further complicate progress. Ethical concerns about the impact of automation and AI on employment must be transparently addressed. Smart buildings focus on energy efficiency, automation, occupant comfort, technology integration, and data security. Sustainable buildings emphasize energy performance, water efficiency, responsible material use, and thoughtful site selection.

Resilient buildings, with disaster preparedness, adaptive design, and community engagement, prepare us for unforeseen challenges. By tackling these issues, the AEC industry can redefine construction, aligning it with community well-being and values.

5.2 Practical implications

Capitalizing on the opportunities involving innovative materials, advanced technologies, resilient design, circular economy principles, occupant well-being, and community engagement requires a collaborative approach, embracing technological advancements, policy support, financial incentives, and a collective commitment to sustainable and resilient construction practices. Addressing the challenges involving human-centric technological integration, skilled workforce, regulatory compliance, lack of standards and best practices demands collaboration among stakeholders, supportive policies, investment in research and development, educational initiatives, and a commitment to innovation and sustainable practices within the AEC industry.

Shifting focus to the broader implications of the findings, it is crucial to underscore the significant contributions this study makes to the field. By addressing the critical research gap in the exploration of Construction 5.0, the research not only advances the theoretical understanding of this paradigm but also provides practical insights with resonance in the AEC industry. The outcomes of the study serve as a compass for industry practitioners, policymakers, and researchers alike, guiding them towards a more informed and strategic approach to embracing Construction 5.0. Specifically, the findings shed light on how adopting human-centric technology, sustaining resilience, and maintaining sustainability within the AEC industry can act as catalysts for overcoming challenges and seizing opportunities inherent in Construction 5.0. This transformative potential extends beyond theoretical frameworks, offering tangible benefits for the built environment. Through a detailed exploration of the methodological rigor and the impactful nature of the findings, this study aims to convey the depth and significance in unraveling the complexities of Construction 5.0 and charting a course for its meaningful integration into the future of construction practices.

Smart buildings represent the pinnacle of modern construction, embodying resilience and sustainability through advanced technology and human-centric design. Construction 5.0, characterized by the integration of intelligent automation, adaptive systems, and sustainable practices, addresses the growing need for resilient and sustainable urban infrastructure.

Human-Centric Automation and Integration are core components of Construction 5.0, ensuring that technological advancements serve human needs and enhance the built environment. In smart buildings, this translates to:

- (1) *Enhanced user experience:* Smart buildings prioritize the comfort and well-being of occupants through adaptive environments. Automation systems regulate temperature, lighting, and air quality based on real-time data, creating healthier and more comfortable living and working spaces.
- (2) *Increased productivity and efficiency:* Automation reduces manual intervention in building operations, leading to more efficient energy use and lower operational costs. Intelligent systems monitor and manage energy consumption, water usage, and other resources, promoting sustainability.
- (3) *Technology integration:* Seamless integration of IoT devices, sensors, and AI allows for comprehensive monitoring and management of building systems. This integration enhances the building's functionality and user experience.

Resilient and Adaptive Industrial Systems for Construction 5.0 are vital for the longevity and robustness of smart buildings. These systems are designed to withstand and recover from various disruptions, ensuring continuous operation:

- (1) *Structural resilience*: Smart buildings are constructed with materials and designs that can withstand natural disasters such as earthquakes, floods, and storms. Adaptive building systems can modify structural behavior in response to environmental changes.
- (2) *Operational continuity*: Smart buildings are equipped with backup systems and redundancies to maintain operations during emergencies. For example, automated energy management systems can switch to alternative power sources during outages, ensuring minimal disruption.
- (3) *Dynamic adaptation*: Smart buildings can adapt to changing conditions over time. This includes modifying energy consumption patterns, adjusting environmental controls, and updating security protocols based on real-time data and predictive analytics.

Sustainable and Integrated Practices for Construction 5.0 are at the heart of smart building design and operation, focusing on minimizing environmental impact and promoting resource efficiency:

- (1) *Energy efficiency*: Smart buildings utilize advanced energy management systems to optimize energy use. This includes integrating renewable energy sources, such as solar panels and wind turbines, and employing energy-saving technologies like LED lighting and high-efficiency HVAC systems.
- (2) *Indoor environmental quality*: Smart buildings prioritize indoor air quality, natural lighting, and acoustics to create healthy indoor environments. Automated systems monitor and adjust air quality, ensuring a comfortable and safe living or working space.
- (3) *Water conservation*: Innovative water management systems in smart buildings reduce water consumption and promote recycling. Technologies such as rainwater harvesting, greywater recycling, and low-flow fixtures are common practices.
- (4) *Waste reduction*: Smart buildings implement waste management systems that promote recycling and minimize landfill use. Automated waste sorting and composting systems help manage waste sustainably.

Opportunities through Technology, Sustainability, and Human-Centric Approaches highlight the potential for smart buildings to lead the way in Construction 5.0.

- (1) *Technological innovation*: Advances in IoT, AI, and blockchain provide new opportunities for smart buildings to enhance resilience and sustainability. For example, IoT sensors can monitor structural health, while AI algorithms optimize resource use and predictive maintenance.
- (2) *Sustainable development*: Smart buildings contribute to sustainable urban development by reducing carbon footprints and promoting eco-friendly practices. This aligns with global sustainability goals, such as the United Nations Sustainable Development Goals (SDGs).
- (3) *Human-centric design*: Integrating human-centric design principles ensures that smart buildings meet the needs of occupants. This includes ergonomic design, accessibility features, and personalized environmental controls.

Overcoming Implementation Challenges is essential for realizing the full potential of smart buildings in Construction 5.0. Key challenges and strategies include.

- (1) *High initial costs*: The initial investment for smart building technologies can be high. Strategies to overcome this include leveraging public-private partnerships, green financing, and demonstrating long-term cost savings through pilot projects.

- (2) *Skilled workforce*: Implementing and maintaining smart building technologies requires a skilled workforce. Investing in training programs and education initiatives can bridge the skills gap.
- (3) *Regulatory barriers*: Navigating complex regulatory environments can be challenging. Advocating for supportive policies and standards, and engaging with regulatory bodies, can facilitate smoother implementation.
- (4) *Data security and privacy*: Ensuring the security and privacy of data collected by smart building systems is crucial. Implementing robust cybersecurity measures and adhering to data protection regulations are essential practices.

Integrated Sustainability and Resilience are achieved by embedding sustainable and resilient practices into every aspect of smart building design and operations.

- (1) *Holistic design*: Smart buildings are designed with a holistic approach that integrates sustainability and resilience from the outset. This includes site selection, materials, construction methods, and operational strategies.
- (2) *Real-time monitoring and management*: Continuous monitoring of building systems through IoT sensors and data analytics enables real-time adjustments to enhance performance and resilience.
- (3) *Community and ecosystem integration*: Smart buildings are not isolated entities; they interact with their surrounding communities and ecosystems. This includes supporting local economies, enhancing biodiversity through green spaces, and participating in community resilience initiatives.

Sample statement of Construction 5.0 for implementation of smart, sustainable and resilient buildings is shown in [Table 9](#).

In summary, the proposed method of evaluating cause-and-effect connections between various factors, such as human-centric technology, resilience, sustainability, and challenges in the AEC industry for facilitating Construction 5.0, provides a comprehensive understanding of the intricate dynamics shaping the future of construction. The importance of these findings transcends the immediate benefits and delves into the overarching theme of interconnectedness among these factors. The study underscores that the successful realization of intelligent, sustainable, and resilient buildings hinges on a holistic approach prioritizing human needs, environmental responsibility, and technological innovation. The challenges identified, including high initial costs, funding hurdles, and the need for a skilled workforce, emphasize the complexity of this transformative journey. Addressing these challenges transparently and effectively becomes imperative, necessitating innovative financial models, comprehensive training programs, and ethical considerations. By navigating these multifaceted dynamics, the AEC industry has a unique opportunity not only to redefine construction practices but also to create a built environment that resonates deeply with the values and well-being of the communities it serves. In essence, the study provides valuable insights into the multifaceted nature of Construction 5.0, emphasizing the need for a harmonious coexistence of humans and technology to achieve a smarter, more sustainable, and resilient built environment. [Figure 3](#) illustrates the dynamic interplay between the core concepts of Human-centric Technology, Resilience, Sustainability, Opportunities, and Challenges within the framework of Construction 5.0. This figure not only depicts the interconnection between these elements but also highlights their collective impact on the implementation of smart, sustainable, and resilient buildings. By visualizing these relationships, the figure supports the study's exploration of how these factors synergize to facilitate Construction 5.0, emphasizing the pathways through which opportunities can be seized and challenges overcome to achieve the desired outcomes.

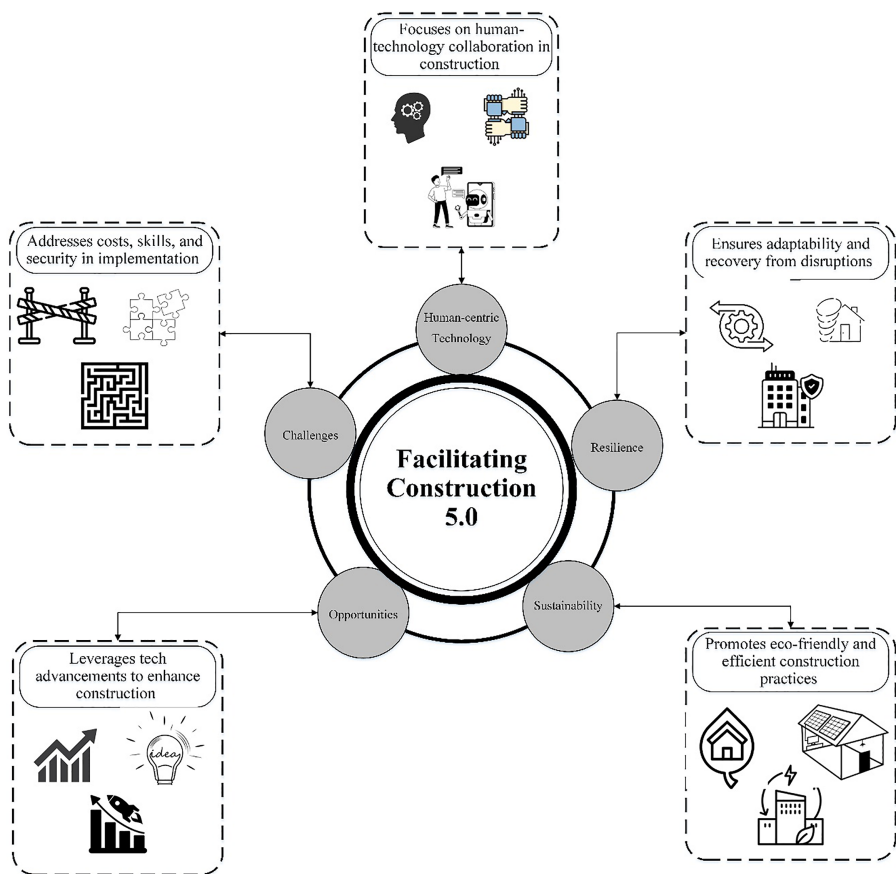
Table 9. Sample statement of Construction 5.0 for implementation of smart, sustainable and resilient buildings

	Process	Opportunities	Challenges
Human-centric technology for Construction 5.0	Collaborative robots (Cobots) working alongside human workers assist in repetitive or physically demanding tasks, improving efficiency and reducing the risk of accidents Advanced security systems, including surveillance, access control, and cybersecurity measures, ensure the safety of occupants and the integrity of building systems	AR technologies provide immersive training environments and simulations, allowing workers to learn in a safe, controlled setting, reducing on-site risks and enhancing skills Advances in IoT, AI, and blockchain provide new opportunities for smart buildings to enhance resilience and sustainability	Necessity for upskilling the human workforce to effectively utilize Cobots Ensuring the security and privacy of data collected by smart building systems is crucial. Implementing robust cybersecurity measures and adhering to data protection regulations are essential practices
Resilience for Construction 5.0	Conducting a comprehensive risk assessment to identify potential risks and their impact on projects Adaptive building systems can modify structural behavior in response to environmental changes	Developing mitigation strategies and plans to address the identified risks, aiming to minimize their effects on construction activities Smart buildings adapting to changing conditions over time, modifying energy consumption patterns, adjusting environmental controls, and updating security protocols based on real-time data and predictive analytics	Formulating effective response plans necessitates a deep understanding of various threats, which can be challenging in dynamic and unpredictable environments Adaptation techniques and mitigation measures necessitates the comprehensive collection, analysis, documentation, regular updating, and practical application of data in smart building systems
Sustainability for Construction 5.0	Choosing eco-friendly and sustainable materials for construction, considering their environmental impact, durability, recyclability, and embodied energy Creating smart building structures and systems that can withstand the test of time while minimizing their ecological footprint	Conducting lifecycle assessments to evaluate the environmental impact of materials throughout their lifespan Optimizing resource efficiency, reducing greenhouse gas emissions, and utilizing renewable and non-polluting resources in smart building systems	Limited availability of sustainable materials or technologies in the market might restrict options for construction projects, leading to compromises in sustainability goals Need of a holistic approach for design of smart build systems integrating sustainability and resilience from the outset

Source(s): Table created by authors

5.3 Limitations and future study

This study has certain limitations, including a relatively small sample size, a limited exploration of parameters, and a narrow focus on specific regions conducted for data collection. The research highlights the need to thoroughly investigate opportunities and challenges in integrating advanced technologies with human-centered approaches, sustainable practices, and resilience considerations to realize the Construction 5.0 paradigm. Future studies could expand on this framework by exploring additional capabilities in specific application areas to enhance the implementation of smart, sustainable, and resilient buildings



Source(s): Figure created by authors

Figure 3. Facilitating Construction 5.0 for smart, sustainable and resilient buildings: opportunities and challenges for implementation

within the Construction 5.0 system. To gain a better understanding of future Construction 5.0 research and implementation, it would be beneficial to establish a well-defined reference architecture for planning, design and construction of smart, sustainable, and resilient buildings. The Construction 5.0 perspective emphasizes the importance of human-machine cognitive cooperation in innovating, designing, and constructing smart, sustainable, and resilient buildings. Enriching the Construction 5.0 paradigm could involve further research on the suggested topics or new ones, particularly those related to the highlighted opportunities and challenges such as promoting acceptance and adaptability during implementation of smart, sustainable, and resilient buildings and developing regulatory and policy frameworks for the AEC industry.

6. Conclusions

This study explored the opportunities and challenges for facilitating Construction 5.0 and its potential to implement smart, sustainable, and resilient buildings. It presented the human-centric technology, sustainability, resilience for facilitating Construction 5.0 and associated

opportunities and challenges. In this study, the SEM technique was employed to assess the research model and explore the cause-and-effect connections between human-centric technology, sustainability, and resilience of the Construction 5.0 paradigm, opportunities and challenges for facilitating Construction 5.0, and implementing smart, sustainable, and resilient buildings. A total of eight significant hypotheses were put forward and rigorously evaluated. The reliability and validity of the constructs were examined through the measurement of key variables. According to the findings, the factors Motivating Society 5.0, Implementing sustainable building practices, Enforcing resilience and adaptability, and Incorporating smart building features in terms of opportunities, and Establishing regulatory and policy frameworks, Managing scalability, Imposing acceptance and adaptability, and Dealing with ethical concerns in terms of challenges had the highest significance for facilitating Construction 5.0. The correlations between the constructs “Implementing Smart, Sustainable, and Resilient Buildings” and “Opportunities for facilitating Construction 5.0”, and “Implementing Smart, Sustainable, and Resilient Buildings and “Challenges for facilitating Construction 5.0” had the highest values validating the empirical modeling work. Hypothesis 7 involving “Seizing the opportunities for facilitating Construction 5.0 stimulates the implementation of Smart, Sustainable and Resilient Buildings” and Hypothesis 8 “Overcoming the challenges for facilitating Construction 5.0 endorses the implementation of Smart, Sustainable and Resilient Buildings” significantly and positively influenced Implementing Smart, Sustainable and Resilient Buildings. Embracing human-centric technology, upholding resilience, and ensuring sustainability within the AEC industry allows us to capitalize on the prospects and tackle the challenges in advancing Construction 5.0 for the realization of intelligent, sustainable, and resilient buildings. In the grander scheme, the AEC sector, as it drives Construction 5.0, possesses the capability to reimagine the construction landscape. This entails creating a built environment that not only embodies intelligence, sustainability, and resilience but also forms a profound connection with the welfare and principles of the communities it serves.

References

- Adel, A. (2023), “Unlocking the future: fostering human–machine collaboration and driving intelligent automation through industry 5.0 in smart cities”, *Smart Cities*, Vol. 6 No. 5, pp. 2742-2782, doi: [10.3390/smartcities6050124](https://doi.org/10.3390/smartcities6050124).
- Al-Kodmany, K. (2022), “Sustainable high-rise buildings: toward resilient built environment”, *Frontiers in Sustainable Cities*, Vol. 4, 782007, doi: [10.3389/frsc.2022.782007](https://doi.org/10.3389/frsc.2022.782007).
- Almusaed, A. and Yitmen, I. (2023), “Architectural reply for smart building design concepts based on artificial intelligence simulation models and digital twins”, *Sustainability*, Vol. 15 No. 6, p. 4955, doi: [10.3390/su15064955](https://doi.org/10.3390/su15064955).
- Almusaed, A., Yitmen, I. and Almssad, A. (2023), “Enhancing smart home design with AI models: a case study of living spaces implementation review”, *Energies*, Vol. 16 No. 6, p. 2636, doi: [10.3390/en16062636](https://doi.org/10.3390/en16062636).
- Baicun, W. and Yuan, X. (2022), “Human-centered: intelligent manufacturing: overview and perspectives”, *Strategic Study of CAE*, Vol. 22, pp. 139-146, doi: [10.15302/J-SSCAE-2020.04.020](https://doi.org/10.15302/J-SSCAE-2020.04.020).
- Baig, M.I. and Yadegaridehkordi, E. (2024), “Industry 5.0 applications for sustainability: a systematic review and future research directions”, *Sustainable Development*, Vol. 32 No. 1, pp. 662-681, doi: [10.1002/sd.2699](https://doi.org/10.1002/sd.2699).
- Bednar, P.M. and Welch, C. (2020), “Socio-technical perspectives on smart working: creating meaningful and sustainable systems”, *Information Systems Frontiers*, Vol. 22 No. 2, pp. 281-298, doi: [10.1007/s10796-019-09921-1](https://doi.org/10.1007/s10796-019-09921-1).
- Breque, M., de Nul, L. and Petridis, A. (2021), *Industry 5.0: towards a Sustainable, Human-Centric and Resilient European Industry*, European Commission, Directorate-General for Research and Innovation, Luxembourg.

- Colla, V., Matino, R., Schröder, A.J., Schivalocchi, M. and Romaniello, L. (2021), "Human-centered robotic development in the steel shop: improving health, safety and digital skills at the workplace", *Metals*, Vol. 11 No. 4, p. 647, doi: [10.3390/met11040647](https://doi.org/10.3390/met11040647).
- Demir, K.A., Döven, G. and Sezen, B. (2019), "Industry 5.0 and human-robot co-working", *Procedia Computer Science*, Vol. 158, pp. 688-695, doi: [10.1016/j.procs.2019.09.104](https://doi.org/10.1016/j.procs.2019.09.104).
- Du, J., Wang, W., Lou, T. and Zhou, H. (2023), "Resilience and sustainability-informed probabilistic multi-criteria decision-making framework for design solutions selection", *Journal of Building Engineering*, Vol. 71, 106421, doi: [10.1016/j.jobe.2023.106421](https://doi.org/10.1016/j.jobe.2023.106421).
- Fonda, E. and Meneghetti, A. (2022), "The human-centric SMED", *Sustainability*, Vol. 14 No. 1, p. 514, doi: [10.3390/su14010514](https://doi.org/10.3390/su14010514).
- Fraga-Lamas, P., Fernández-Caramés, T.M., da Cruz, A.M.R. and Lopes, S.I. (2024), "An overview of blockchain for Industry 5.0: towards human-centric, sustainable and resilient applications", *IEEE Access*, Vol. 12, pp. 116162-116201, doi: [10.1109/ACCESS.2024.3435374](https://doi.org/10.1109/ACCESS.2024.3435374).
- Fukuda, K. (2020), "Science, technology and innovation ecosystem transformation toward society 5.0", *International Journal of Production Economics*, Vol. 220, 107460, doi: [10.1016/j.ijpe.2019.07.033](https://doi.org/10.1016/j.ijpe.2019.07.033).
- Gholami, H., Abu, F., Lee, J.K.Y., Karganroudi, S.S. and Sharif, S. (2021), "Sustainable manufacturing 4.0—pathways and practices", *Sustainability*, Vol. 13 No. 24, 13956, doi: [10.3390/su132413956](https://doi.org/10.3390/su132413956).
- Hao, H., Bi, K., Chen, W., Pham, T.M. and Li, J. (2023), "Towards next generation design of sustainable, durable, multi-hazard resistant, resilient, and smart civil engineering structures", *Engineering Structures*, Vol. 277, 115477, doi: [10.1016/j.engstruct.2022.115477](https://doi.org/10.1016/j.engstruct.2022.115477).
- He, W., Li, Z. and Chen, C.L.P. (2017), "A survey of human-centered intelligent robots: issues and challenges", *IEEE/CAA Journal of Automatica Sinica*, Vol. 4, pp. 602-609, doi: [10.1109/JAS.2017.7510604](https://doi.org/10.1109/JAS.2017.7510604).
- Horvatic, D. and Lipic, T. (2021), "Human-centric AI: the symbiosis of human and artificial intelligence", *Entropy*, Vol. 23 No. 3, p. 332, doi: [10.3390/e23030332](https://doi.org/10.3390/e23030332).
- How, M., Cheah, S.M., Chan, Y.J., Khor, A.C. and Say, E.M.P. (2020), "Artificial intelligence-enhanced decision support for informing global sustainable development: a human-centric AI-thinking approach", *Information*, Vol. 11 No. 1, p. 39, doi: [10.3390/info11010039](https://doi.org/10.3390/info11010039).
- Huang, S., Wang, B., Li, X., Zheng, P., Mourtzis, D. and Wang, L. (2022), "Industry 5.0 and society 5.0—comparison, complementation and co-evolution", *Journal of Manufacturing Systems*, Vol. 64, pp. 424-428, doi: [10.1016/j.jmsy.2022.07.010](https://doi.org/10.1016/j.jmsy.2022.07.010).
- Ikudayisi, A.E., Chan, A.P., Darko, A. and Yomi, M.D. (2023), "Integrated practices in the architecture, engineering, and construction industry: current scope and pathway towards industry 5.0", *Journal of Building Engineering*, Vol. 73, 106788, doi: [10.1016/j.jobe.2023.106788](https://doi.org/10.1016/j.jobe.2023.106788).
- Ivanov, D. (2023), "The Industry 5.0 framework: viability-based integration of the resilience, sustainability, and human-centricity perspectives", *International Journal of Production Research*, Vol. 61 No. 5, pp. 1683-1695, doi: [10.1080/00207543.2022.2118892](https://doi.org/10.1080/00207543.2022.2118892).
- Kadir, B.A. and Broberg, O. (2021), "Human-centered design of work systems in the transition to industry 4.0", *Applied Ergonomics*, Vol. 92, 103334, doi: [10.1016/j.apergo.2020.103334](https://doi.org/10.1016/j.apergo.2020.103334).
- Kong, X.T.R., Luo, H., Huang, G.Q. and Yang, X. (2019), "Industrial wearable system: the human-centric empowering technology in Industry 4.0", *Journal of Intelligent Manufacturing*, Vol. 30 No. 8, pp. 2853-2869, doi: [10.1007/s10845-018-1416-9](https://doi.org/10.1007/s10845-018-1416-9).
- Kor, M., Yitmen, I. and Alizadehsalehi, S. (2023), "An investigation for integration of deep learning and digital twins towards Construction 4.0", *Smart and Sustainable Built Environment*, Vol. 12 No. 3, pp. 461-487, doi: [10.1108/SASBE-08-2021-0148](https://doi.org/10.1108/SASBE-08-2021-0148).
- Kravets, A.G., Bolshakov, A.A. and Shcherbakov, M. (2021), *Society 5.0*, Springer International Publishing AG, Cham, ISBN 978-3-030-63562-6.
- Kusi-Sarpong, S., Gupta, H. and Sarkis, J. (2019), "A supply chain sustainability innovation framework and evaluation methodology", *International Journal of Production Research*, Vol. 57 No. 7, p. 1, doi: [10.1080/00207543.2018.1518607](https://doi.org/10.1080/00207543.2018.1518607).

- Leng, J., Sha, W., Wang, B., Zheng, P., Zhuang, C., Liu, Q., Wuest, T., Mourtzis, D. and Wang, L. (2022), "Industry 5.0: prospect and retrospect", *Journal of Manufacturing Systems*, Vol. 65, pp. 279-295, doi: [10.1016/j.jmsy.2022.09.017](https://doi.org/10.1016/j.jmsy.2022.09.017).
- Li, R., Satchwell, A.J., Finn, D., Christensen, T.H., Kummert, M., Le Dréau, J., Lopes, R.A., Madsen, H., Salom, J., Henze, G. and Wittchen, K. (2022), "Ten questions concerning energy flexibility in buildings", *Building and Environment*, Vol. 223, 109461, doi: [10.1016/j.buildenv.2022.109461](https://doi.org/10.1016/j.buildenv.2022.109461).
- Liyanage, M., Braeken, A., Kumar, P. and Ylianttila, M. (2020), *IoT Security: Advances in Authentication*, John Wiley & Sons, Chichester.
- Lu, Y., Adrados, J.S., Chand, S.S. and Wang, L. (2021), "Humans are not machines—anthropocentric human-machine symbiosis for ultra-flexible smart manufacturing", *Engineering*, Vol. 7 No. 6, pp. 734-737, doi: [10.1016/j.eng.2020.09.018](https://doi.org/10.1016/j.eng.2020.09.018).
- Lu, Y., Zheng, H., Chand, S., Xia, W., Liu, Z., Xu, X., Wang, L., Qin, Z. and Bao, J. (2022), "Outlook on human-centric manufacturing towards Industry 5.0", *Journal of Manufacturing Systems*, Vol. 62, pp. 612-627, doi: [10.1016/j.jmsy.2022.02.001](https://doi.org/10.1016/j.jmsy.2022.02.001).
- Maddikunta, P.K.R., Pham, Q.V., Prabadevi, B., Deepa, N., Dev, K., Gadekallu, T.R., Ruby, R. and Liyanage, M. (2022), "Industry 5.0: a survey on enabling technologies and potential applications", *Journal of Industrial Information Integration*, Vol. 26, 100257, doi: [10.1016/j.jii.2021.100257](https://doi.org/10.1016/j.jii.2021.100257).
- Majidi, A., Dwijendra, N.K.A., Muda, I., Chethamrongchai, P., Sivaraman, R. and Hammid, A.T. (2022), "A smart building with integrated energy management: steps toward the creation of a smart city", *Sustainable Energy Technologies and Assessments*, Vol. 53, 102663, doi: [10.1016/j.seta.2022.102663](https://doi.org/10.1016/j.seta.2022.102663).
- Marinelli, M. (2023), "From Industry 4.0 to Construction 5.0: exploring the path towards human-robot collaboration in construction", *Systems*, Vol. 11 No. 3, p. 152, doi: [10.3390/systems11030152](https://doi.org/10.3390/systems11030152).
- Mourtzis, D., Angelopoulos, J. and Panopoulos, N. (2022), "Operator 5.0: a survey on enabling technologies and a framework for digital manufacturing based on extended reality", *Journal of Machine Engineering*, Vol. 22 No. 1, pp. 43-69, doi: [10.36897/jme/147160](https://doi.org/10.36897/jme/147160).
- Mukherjee, S., Baral, M.M., Chittipaka, V., Nagariya, R. and Patel, B.S. (2023), "Achieving organizational performance by integrating industrial Internet of Things in the SMEs: a developing country perspective", *The TQM Journal*, Vol. 36 No. 1, pp. 265-287, doi: [10.1108/TQM-07-2022-0221](https://doi.org/10.1108/TQM-07-2022-0221).
- Musarat, M.A., Irfan, M., Alaloul, W.S., Maqsoom, A. and Ghufra, M. (2023), "A review on the way forward in construction through industrial revolution 5.0", *Sustainability*, Vol. 15 No. 18, 13862, doi: [10.3390/su151813862](https://doi.org/10.3390/su151813862).
- Nahavandi, S. (2019), "Industry 5.0 a human centric solution", *Sustainability*, Vol. 11 No. 16, p. 4371, doi: [10.3390/su11164371](https://doi.org/10.3390/su11164371).
- Nguyen Ngoc, H., Lasa, G. and Iriarte, I. (2022), "Human-centred design in industry 4.0: case study review and opportunities for future research", *Journal of Intelligent Manufacturing*, Vol. 33 No. 1, pp. 35-76, doi: [10.1007/s10845-021-01796-x](https://doi.org/10.1007/s10845-021-01796-x).
- Papetti, A., Gregori, F., Pandolfi, M., Peruzzini, M. and Germani, M. (2020), "A method to improve workers' well-being toward human centered connected factories", *Journal of Computer Design and Engineering*, Vol. 7 No. 5, pp. 630-643, doi: [10.1093/jcde/qwaa047](https://doi.org/10.1093/jcde/qwaa047).
- Porambage, P., Gür, G., Moya Osorio, D.P., Liyanage, M., Gurtov, A. and Ylianttila, M. (2021), "The roadmap to 6G security and privacy", *IEEE Open Journal of the Communications Society*, Vol. 2, pp. 1094-1122, doi: [10.1109/OJCOMS.2021.3078081](https://doi.org/10.1109/OJCOMS.2021.3078081).
- Romero, D. and Stahre, J. (2021), "Towards the resilient operator 5.0: the future of work in smart resilient manufacturing systems", *Procedia CIRP*, Vol. 104, pp. 1089-1094, doi: [10.1016/j.procir.2021.11.183](https://doi.org/10.1016/j.procir.2021.11.183).
- Roostaie, S. and Nawari, N. (2022), "The DEMATEL approach for integrating resilience indicators into building sustainability assessment frameworks", *Building and Environment*, Vol. 207, 108113, doi: [10.1016/j.buildenv.2021.108113](https://doi.org/10.1016/j.buildenv.2021.108113).
- Sharma, R. (2024), "Analysis of Industry 5.0 contributions to sustainable development: from welfare to wellbeing", in *Modern Technologies and Tools Supporting the Development of Industry 5.0*, CRC Press, pp. 259-300, ISBN: 9781003489269.

- Sharma, M., Sehrawat, R., Luthra, S., Daim, T. and Bakry, D. (2022), "Moving towards Industry 5.0 in the pharmaceutical manufacturing sector: challenges and solutions for Germany", *IEEE Transactions on Engineering Management*, Vol. 1, pp. 1-18, doi: [10.1109/TEM.2022.3143466](https://doi.org/10.1109/TEM.2022.3143466).
- Siriwardhana, S. and Moehler, R. (2024), "Mastering the skills of Construction 4.0: a review of the literature using science mapping", *Smart and Sustainable Built Environment*, Vol. 13 No. 4, pp. 989-1014, doi: [10.1108/SASBE-03-2023-0045](https://doi.org/10.1108/SASBE-03-2023-0045).
- Stahl, B.C. (2021), "Ethical issues of AI", in *Artificial Intelligence for a Better Future*, Vol. 35, pp. 35-53, doi: [10.1007/978-3-030-69978-9_4](https://doi.org/10.1007/978-3-030-69978-9_4).
- Turner, C., Oyekan, J., Garn, W., Duggan, C. and Abdou, K. (2022), "Industry 5.0 and the circular economy: utilizing LCA with intelligent products", *Sustainability*, Vol. 14 No. 22, 14847, doi: [10.3390/su142214847](https://doi.org/10.3390/su142214847).
- Ullah, F. (2022), "Smart Tech 4.0 in the built environment: applications of disruptive digital technologies in smart cities, construction, and real estate", *Buildings*, Vol. 12 No. 10, p. 1516, doi: [10.3390/buildings12101516](https://doi.org/10.3390/buildings12101516).
- Ullah, F., Olatunji, O. and Qayyum, S. (2024), "A scoping review of green Internet of Things in construction and smart cities: current applications, adoption strategies and future directions", *Smart and Sustainable Built Environment*, vol. ahead-of-print no. ahead-of-print, doi: [10.1108/SASBE-11-2023-0349](https://doi.org/10.1108/SASBE-11-2023-0349).
- Venkatesh, V.G., Kang, K., Wang, B., Zhong, R.Y. and Zhang, A. (2020), "System architecture for blockchain-based transparency of supply chain social sustainability", *Robotics and Computer-Integrated Manufacturing*, Vol. 63, 101896, doi: [10.1016/j.rcim.2019.101896](https://doi.org/10.1016/j.rcim.2019.101896).
- Vesnic-Alujevic, L., Nascimento, S. and Polvora, A. (2020), "Societal and ethical impacts of artificial intelligence: critical notes on European policy frameworks", *Telecommunications Policy*, Vol. 44 No. 6, 101961, doi: [10.1016/j.telpol.2020.101961](https://doi.org/10.1016/j.telpol.2020.101961).
- Wang, B., Zheng, P., Yin, Y., Shih, A. and Wang, L. (2022), "Toward human-centric smart manufacturing: a human-cyber-physical systems (HCPS) perspective", *Journal of Manufacturing Systems*, Vol. 63, pp. 471-490, doi: [10.1016/j.jmsy.2022.05.005](https://doi.org/10.1016/j.jmsy.2022.05.005).
- Xiong, B., Skitmore, M. and Xia, B. (2015), "A critical review of structural equation modeling applications in construction research", *Automation in Construction*, Vol. 49, pp. 59-70, doi: [10.1016/j.autcon.2014.09.006](https://doi.org/10.1016/j.autcon.2014.09.006).
- Xu, X., Lu, Y., Vogel-Heuser, B. and Wang, L. (2021), "Industry 4.0 and industry 5.0—inception, conception, and perception", *Journal of Manufacturing Systems*, Vol. 61, pp. 530-535, doi: [10.1016/j.jmsy.2021.10.006](https://doi.org/10.1016/j.jmsy.2021.10.006).
- Yitmen, I., Almusaed, A. and Alizadehsalehi, S. (2023), "Investigating the causal relationships among enablers of the construction 5.0 paradigm: integration of operator 5.0 and society 5.0 with human-centricity, sustainability, and resilience", *Sustainability*, Vol. 15 No. 11, p. 9105, doi: [10.3390/su15119105](https://doi.org/10.3390/su15119105).
- Zizic, M.C., Mladineo, M., Gjeldum, N. and Celent, L. (2022), "From Industry 4.0 towards Industry 5.0: a review and analysis of paradigm shift for the people, organization and technology", *Energies*, Vol. 15 No. 14, p. 5221, doi: [10.3390/en15145221](https://doi.org/10.3390/en15145221).

Further reading

- Felicioni, L., Lupíšek, A. and Gaspari, J. (2023), "Exploring the common ground of sustainability and resilience in the building sector: a systematic literature review and analysis of building rating systems", *Sustainability*, Vol. 15 No. 1, p. 884, doi: [10.3390/su15010884](https://doi.org/10.3390/su15010884).
- Mansour, H., Aminudin, E. and Mansour, T. (2023), "Implementing industry 4.0 in the construction industry—strategic readiness perspective", *International Journal of Construction Management*, Vol. 23 No. 9, pp. 1457-1470, doi: [10.1080/15623599.2021.1975351](https://doi.org/10.1080/15623599.2021.1975351).
- Touriki, F.E., Benkhathi, I., Kamble, S.S., Belhadi, A. and El fezazi, S. (2021), "An integrated smart, green, resilient, and lean manufacturing framework: a literature review and future research directions", *Journal of Cleaner Production*, Vol. 319, 128691, doi: [10.1016/j.jclepro.2021.128691](https://doi.org/10.1016/j.jclepro.2021.128691).

Appendix A

Questionnaire Survey

Your profession:

Your main technological area of expertise:

The number of years you have been working in the mentioned field:

The company's name:

The company size (0–50 Employees—Small, 50–250 Employees—Medium, >250 Employees—Large):

From what country are you mainly operating?

“To what extent do you agree with the following items describing your organization's view on Construction 5.0 for Smart, Sustainable and Resilient Buildings? (1 = strongly disagree; 5 = strongly agree).”

No	Questions	Likert Scale Values				
		1	2	3	4	5
		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
	<i>Human-centric technology for Construction 5.0</i>					
1	Machines and robots not replacing humans in the industry					
2	Necessity of human involvement for achieving automation and digitization					
3	Prioritization of human needs and interests as the foundation of the production process					
4	Demand of intelligent robots understanding the interconnected relationships between humans and machines in unstructured environments					
5	Autonomously ensuring the security and stability of communication networks that serve as social infrastructure					
	<i>Resilience for Construction 5.0</i>					
6	Re-thinking existing working methods and approaches					
7	Reducing the vulnerability of supply chains					
8	Focusing on the ability of firms to cope with external uncertainties					
9	Focusing on the resilience of a wider range of industrial systems					
10	Technology systems and solutions prioritizing stability over resilience and providing more prevalent and mass-automation solutions					
	<i>Sustainability for Construction 5.0</i>					
11	Implementing the sustainable construction vision regarding the decentralized connection of socialized production resources and products to deliver mass-individualized products and services					
12	Balancing the three pillars (economy, environment, and society) in different stages to achieve success in construction					
13	Providing information to customers on social sustainability					
14	Traceability in multi-tier supply chains through blockchain technology					
15	Achieving Construction 5.0 with greater quantity, faster speed, better quality, and cost savings through sustainable practices					
	<i>Opportunities for facilitating Construction 5.0</i>					
16	Implementing advancements in technology					
17	Stimulating Operator 5.0					
18	Motivating Society 5.0					
19	Adopting circular economy					
20	Implementing sustainable building practices					
21	Enforcing resilience and adaptability					
22	Incorporating Smart Building Features					

	<i>Challenges in facilitating Construction 5.0</i>
23	Facing high initial costs and funding
24	Necessity of skilled workforce
25	Maintaining data security and privacy
26	Establishing regulatory and policy frameworks
27	Managing scalability
28	Imposing acceptance and adaptability
29	Dealing with ethical concerns
	<i>Implementing Smart, Sustainable, and Resilient Buildings</i>
	<i>Smart Buildings</i>
30	Energy efficiency
31	Automation and control
32	Occupant comfort
33	Technology integration
34	Data utilization
35	Security and safety
	<i>Sustainable Buildings</i>
36	Energy performance
37	Water efficiency
38	Materials and resources
39	Indoor environmental quality
40	Site selection and land Use
41	Transportation and access
	<i>Resilient Buildings</i>
42	Disaster preparedness
43	Adaptive design
44	Backup systems
45	Climate resilience
46	Structural integrity
47	Community engagement

Source(s): Table created by authors

Corresponding author

Ibrahim Yitmen can be contacted at: ibrahim.yitmen@ju.se