

USE OF ENABLING TECHNOLOGIES WITH INDUSTRY 5.0 TO ALIGN WITH SUSTAINABILITY IN THE CONSTRUCTION INDUSTRY

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Abstract: The shifting industrial landscape of Industry 5.0 demands adaptability to technological advancements, emphasising human-machine interaction. The enabling technologies facilitate the transition from Industry 4.0 to Industry 5.0, ensuring technological advancements align with human well-being and sustainability. However, limited literature exists on their application with Industry 5.0 in construction, particularly focusing on sustainability. Addressing this gap, this study investigates how to use enabling technologies with Industry 5.0 to align with sustainability in the construction industry, through a qualitative research approach, employing two rounds of semi-structured expert interviews using the Delphi technique. Manual content analysis was used to analyse the empirical data. Findings revealed that human-centricity, sustainability, and resilience are key elements of Industry 5.0 validating their applicability in construction. This study further highlights nine enabling technologies, including Artificial Intelligence, Collaborative Robots, and Digital Twins as the most impactful for transforming the construction to Industry 5.0. Detailed insights were gathered on leveraging these technologies with each Industry 5.0 element. The findings underscore the importance of integrating these advanced technologies to improve efficiency, safety, and sustainability in construction projects. This research provides strategic insights for industry stakeholders to adopt Industry 5.0 principles, promoting smarter, more resilient, and sustainable construction practices.

Keywords: *Key elements of Industry 5.0; Enabling Technologies; Sustainability; Construction Industry; Delphi Technique*

1. Introduction

The concept of digitization gained popularity with the evolution of Industry 4.0, which originated in Germany in 2011 as a technology-driven concept centered on Cyber-Physical Systems (CPS) aimed at creating intelligent factory environments (Marinelli, 2023). Despite its advancements, Industry 4.0 has been critiqued for its insufficient focus on the human factor, sustainability, and responsibility (Narkhede et al., 2024). Meanwhile, the European Commission introduced Industry 5.0 in 2021, which is a value-driven concept focusing on human-centricity, sustainability, and resilience (Xu et al., 2021). Industry 5.0 is expected to increase customer satisfaction and production efficiency (Maddikunta et al., 2022), through the collaborative work paradigm of human-robot collaboration (HRC) to reintroduce the human aspect into production (Jamil et al., 2024). This approach leverages technology to create more adaptable production environments for workers, while promoting sustainability and circularity (Breque et al., 2021).

Industry 5.0 can be identified as an indication of addressing infrastructural resilience, environmental, and employee concerns in industrial settings, focusing on human-centric technology development and environmental goals (Turner et al., 2022). Indeed, human-centricity, sustainability, and resilience are interpreted as the three core elements of Industry 5.0 (Breque et al., 2021; Ivanov, 2023). This is also supported by Xu et al. (2021) as three interrelated core values on which Industry 5.0 is centered. In order to enforce Industry 5.0 core values, it has identified supporting technologies such as Edge Computing (EC), Digital Twin (DT), Internet of Everything (IoE), Big Data, Collaborative Robots (Cobots), and Blockchain (BC) (Mourtzis et al., 2022). These are identified as enabling technologies of Industry 5.0 (Mahiri et al., 2023). These technological trends enable the industry to boost production, deliver personalised products to customers, and facilitate interaction between humans and machines (Yu & Sun, 2024).

Although the world is becoming more digital, balancing the growth of all territories including social and sustainable aspects, is crucial (Satyro et al., 2022). Digital transformation has adversely affected sustainability through environmental pollution and depletion of non-renewable resources (Pereira & Santos, 2023). Meanwhile, Industry 5.0 evolved to mitigate the negative impacts of the digitalised industry while enhancing sustainability (Xu et al., 2021). In fact, Industry 5.0 paradigm has a great impact on technology integration and the building construction process (Ikudayisi et al., 2023). Thus, there is a practical need for an in-depth investigation of how enabling technologies can be used with core elements of Industry 5.0 to align with sustainability in the construction sector. Considering the theoretical need, previous studies have discussed Industry 4.0 with sustainability (Balasubramanian et al., 2021), the transition from Industry 4.0 to Industry 5.0 (Xu et al., 2021), the human factor in Industry 5.0 (Nahavandi, 2019), Industry 5.0 in the construction industry (Marinelli, 2023), and applications of Industry 5.0 (Tunji-Olayeni et al., 2024). However, there are no sufficient studies on exploring the

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applicability of enabling technologies in construction with Industry 5.0 elements to enhance sustainability. Given the above-mentioned industry imperatives and the lack of theoretical underpinnings, this study aims to investigate how to use enabling technologies with Industry 5.0 to align with sustainability in the construction industry. Its objectives are, to identify the key elements of Industry 5.0, to investigate the enabling technologies which can be used with each element of Industry 5.0 to align with sustainability, and to investigate how to use the enabling technologies with each element of Industry 5.0 to align with sustainability in the construction industry. This paper encompasses an introduction to the research, a comprehensive literature review, research methodology, research findings, discussion, and concluding remarks.

2. Literature Review

This section provides a detailed overview of Industry 4.0 and 5.0 in the construction industry. It outlines the key elements and enabling technologies of Industry 5.0, emphasising the sustainable aspects inherent in both industrial revolutions.

2.1. INDUSTRIAL REVOLUTIONS AND CONSTRUCTION INDUSTRY: INDUSTRY 5.0 AND 4.0

The industrialisation era began in the 1700s, with the first revolution introducing the mechanisation of production powered by water and steam, and the second revolution in the 1870s with electric power and mass production (Alaloul et al., 2020). Later in 1969, the third industrial revolution brought electronics, semi-automation, and information technology (Maddikunta et al., 2022). In 2011, Industry 4.0 was initiated, focusing on smart manufacturing with CPS for improved efficiency and automation (Kozlovska et al., 2021). Emerging digital technologies in Industry 4.0, have fostered 'digital innovation' in the global construction sector (Balasubramanian et al., 2021). The term Construction 4.0 emerged to reflect the interest in using Artificial Intelligence (AI) and Machine Learning (ML) technologies in the construction industry (Kozlovska et al., 2021). Construction 4.0 is defined as a technological advancement that improves the time, cost, and quality aspects of construction projects, including Virtual Reality (VR), Augmented Reality (AR), Building Information Modelling (BIM), prefabrication, and off-site construction (Heijden, 2023). Further, it explores how technological advancements affect the built environment, emphasising how crucial it is to maintain resilience and sustainability over the long run (Kozlovska et al., 2021).

Undoubtedly, Industry 5.0 paradigm has a great impact on technology integration and the building construction process (Ikudayisi et al., 2023). Heijden (2023) suggests that perhaps the construction industry can skip the fourth revolution and directly embrace Industry 5.0 due to its balanced approach to integrating human elements with technology (Marinelli, 2023). However, the concept of 'Construction 5.0' is not yet widely accepted as the future revolution of the construction industry (Yitmen et al., 2023). For Construction 5.0 to be successful, it should focus on human-centric applications, meet industry needs, and align with Industry 5.0 principles (Marinelli, 2023). Key challenges in adopting Industry 5.0 in construction include a lack of technical skills, insufficient data for decision-making, and security issues in human-machine collaboration (Musarat et al., 2023). Despite these challenges, Industry 5.0 aims to enhance efficiency by incorporating human-centric, sustainable, and resilience concepts (Nahavandi, 2019).

2.1.1. Key elements of Industry 5.0

European Commission declares human-centricity, sustainability, and resilience, as three key elements of Industry 5.0 (Brequé et al., 2021). Nevertheless, researchers have adopted different terminologies to describe these elements. The majority of the authors have described them as "key elements" (Atif, 2023; Poláková et al., 2023), whereas the minority refer to them as core values (Xu et al., 2021), key drivers (Zizic et al., 2022), major pillars (Ivanov, 2023), and core principles (Ghobakhloo et al., 2021). In agreement with the majority, this study identifies them as the 'key elements of Industry 5.0'. Table 1 outlines these elements and highlights key points for each. As per Table 1, it is evident that human centricity, sustainability and resilience, are well established in the literature of Industry 5.0 as the key elements of Industry 5.0. Accordingly, this study also identifies human centricity, sustainability and resilience, as the key elements of Industry 5.0.

Table 1: Key elements of Industry 5.0

Key Elements	Authors (in code)													
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Human-centricity	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Better adaptation of technology to human needs	√	√	√	-	√	√	√	√	√	√	-	√	√	√
Empower workers using digitalization	√	√	√	√	√	√	√	√	√	√	-	-	√	√
Human-machine symbiosis	-	-	√	√	√	-	√	√	√	√	-	√	-	√
Main domains of ergonomics (physical, cognitive and organisational)	√	-	√	√	-	-	-	-	√	-	-	-	√	-
Sustainability	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Efficient usage of energy	-	-	√	-	√	√	√	-	√	√	-	-	√	√
Sustainable supply chain networks	√	-	-	-	√	-	-	-	√	√	-	√	-	-
Develop circular processes for better resource efficiency	-	√	-	-	-	√	-	-	-	√	-	-	√	-
Ethical use of technology	-	-	√	-	-	-	√	-	-	-	-	-	-	√
Increased productivity, speed, quality, and savings using environmentally responsible methods	-	-	-	√	-	-	-	√	√	-	-	√	-	-
Resilience	√	√	√	√	√	√	√	√	√	√	√	√	√	√

Implementation of risk plans and prevention techniques	√	-	√	√	√	√	-	-	√	√	-	√	√	√
Supply chain resilience	-	-	√	√	√	-	√	-	√	√	-	√	-	-
Resilience in the context of technology	-	-	√	√	√	-	-	-	-	√	-	√	-	√
Resilience planning	-	√	-	-	-	-	√	√	-	√	-	-	-	√
A: (Atif, 2023), B: (Xu et al., 2021), C: (Zizic et al., 2022), D: (Yitmen et al., 2023), E: (Ivanov, 2023), F: (Breque et al., 2021), G: (Barata & Kayser, 2023), H: (Poláková et al., 2023), I: (Leng et al., 2022), J: (Ikudayisi et al., 2023), K: (Ghobakhloo et al., 2021), L: (Leng et al., 2023), M: (Mahiri et al., 2023), N: (Mourtzis et al., 2022)														

Although humans are irreplaceable by machines or robots, Industry 4.0 concept focuses on moving customer-centric and service-oriented production towards industrial automation (Atif, 2023). In contrast, Industry 5.0 prioritises human needs and interests, being an entirely human and society-centric approach, viewing workers as investments rather than costs (Mahiri et al., 2023). Human-machine collaboration in Industry 5.0 integrates human creativity with automated systems, enhancing efficiency (Poláková et al., 2023). Mourtzis et al. (2022) term this integration 'humachine,' combining human and machine attributes while maintaining their uniqueness. Simultaneously, Industry 5.0 aims to reduce and prevent waste in the supply chain by balancing economic, social, and environmental aspects (Atif, 2023). Despite the growing focus on sustainability over the past two decades, Industry 5.0 demands a more comprehensive approach emphasising resource efficiency, renewable and non-polluting resource utilisation, and greenhouse gas emission reduction (Ikudayisi et al., 2023). Moreover, Breque et al. (2021) claim that sustainability in Industry 5.0 refers to minimising energy consumption and greenhouse gas emissions to prevent natural resource depletion thereby meeting current needs without compromising future generations. Additionally, Industry 5.0 emphasises resilience, the ability to withstand disruptions and support critical infrastructure, which is vital given the vulnerabilities exposed by events like the Covid-19 outbreak (Breque et al., 2021; Zizic et al., 2022). Resilience requires adaptable production, strategic value chains, and flexible business processes, making it a core element of Industry 5.0 (Xu et al., 2021).

2.1.2. Enabling technologies of Industry 5.0

According to Mahiri et al. (2023), the enabling technologies are required by Industry 5.0 to be human-centric, sustainable, and resilient. Industry 5.0 encompasses enabling technologies such as AI, IoE, DT, EC, Big Data, Cobots, 6G, and BC (Mahiri et al., 2023; Pereira & Santos, 2023) with innovation and cognitive skills to help industries boost production and offer customised products more quickly (Maddikunta et al., 2022; Mourtzis et al., 2022). Further, Industry 5.0 recognises Extended Reality (XR) encompassing AR, VR, and Mixed Reality (MR), offering diverse applications in Industry 5.0 processes (Leng et al., 2022; Mourtzis et al., 2022). In Construction 5.0, AR, VR technologies play a crucial role, with AR overlaying digital information onto the physical world to enhance real-time visualisation, while VR provides a tangible project experience (Grech et al., 2023). Overall, these technologies enable human-robot interaction, creating opportunities and bringing humans back into the factory (Pereira & Santos, 2023).

2.1.3. Sustainable components in industrial revolutions

Implementing Industry 4.0 would aid in the creation of a sustainable supply chain, with reduced waste, energy consumption, cost-effectiveness, and resource utilisation (Jamil et al., 2024). According to Breque et al. (2021) the original principles of sustainability and social fairness are under-focused in Industry 4.0. Considering the pillars of sustainability, although Industry 4.0 technologies have shown a positive impact on economic and environmental sustainability, it is still lacking in terms of social sustainability (Balasubramanian et al., 2021). Ghobakhloo et al. (2021) report that the productivity of Industry 4.0 is accelerating the degradation and depletion of natural resources and contributing to the ongoing crisis of overconsumption and rebound effects. Further, it is argued that Industry 4.0 technologies enhance employee health, safety, and satisfaction by automating repetitive tasks but also pose challenges such as reduced employment, electronic waste, information security risks, and potential quality issues (Bai et al., 2020). Satyro et al. (2022) emphasise that Industry 4.0's social dimension has led to unemployment and increased social inequalities, indicating the need to address these issues to achieve true sustainability. Conversely, Industry 5.0 highlights human-machine collaboration and technology integration while balancing the three pillars of sustainability (Yitmen et al., 2023). Thus, by effectively using technologies with Industry 5.0 principles, the sustainability of the construction sector can be improved.

3. Methodology

A qualitative approach is used to explore topics with limited prior knowledge, aiming to understand phenomena through participant perspectives and observations (Creswell, 2009). This research explores how to use enabling technologies with Industry 5.0 in the construction industry. Given the novelty and the scarcity of expertise in Industry 5.0 area, a qualitative approach appears most suitable. Expert interviews are crucial in qualitative research, especially when linking existing micro and macro analyses is challenging (Soest, 2023). The Delphi technique is a survey method used to reach expert consensus through structured rounds of questionnaires (Fathullah et al., 2023). This study follows the Delphi technique, commonly used to achieve expert agreement on topics requiring in-depth analysis (Meijering et al., 2013). This technique adopts non-probability or purposive sampling with criteria to ensure participants have sufficient expertise (Habibi et al., 2014). Thus, experts were selected using purposive sampling considering their knowledge and experience in the key study areas. Further, this study adopted two rounds of Delphi techniques, because Delphi results often achieve accuracy after two iterations, with many construction-related studies reaching consensus after two or three rounds (Ameyaw et al., 2016). Given the novelty of the study area, most experts selected had relevant academic backgrounds with prior experience as practitioners in the

construction industry. Expert profiles are summarised in Table 2. As illustrated in Table 2, the expert selection criteria adapted evaluates the knowledge and experience in the key research areas: Industry 4.0, Industry 5.0, sustainability and the construction industry, to qualify as an expert. All three criteria used to evaluate in terms of experience, educational and professional qualifications are compulsory, to be declared as an expert in the research context.

Table 2: Expert profiles

Expert Code	Designation	Experience	Construction related B.Sc.	Post Graduate Degree/ M.Sc./ Professional Qualification	Key Expert areas related to the topic	Participation	
		Construction/ Research in Industry 4.0/5.0 > 5 years				DR1	DR2
E01	Academic Researcher/ Quantity Surveyor (QS)	✓	✓	✓	Industry 4.0, BC, BIM, Sustainability	✓	✓
E02	Academic Researcher/ Project Manager	✓	✓	✓	Industry 5.0/ 4.0, AI, Construction Automation, Sustainability	✓	✓
E03	PhD Scholar/ QS	✓	✓	✓	Construction 4.0, Sustainability	✓	✓
E04	Academic Researcher/ QS	✓	✓	✓	Industry 4.0, Sustainability	✓	✓
E05	Procurement Specialist/ Commercial Manager	✓	✓	✓	Industry 5.0/ 4.0, Cloud Computing, IoT, Sustainability	✓	-
E06	Digital Construction Specialist	✓	✓	✓	Industry 5.0/ 4.0, DT, BIM, Construction Automation, Sustainability	✓	✓
E07	General Manager/ QS	✓	✓	✓	Industry 4.0, BIM, Sustainability	✓	✓
E08	Director/ QS	✓	✓	✓	Industry 4.0, Digitalization, BIM, Sustainability	✓	✓
E09	Academic Researcher/ QS	✓	✓	✓	Industry 4.0, Sustainability	✓	✓
E10	Academic Researcher/ QS	✓	✓	✓	Industry 5.0/ 4.0, IoT, AI, Sustainability	✓	✓
E11	Software Engineer/ QS	✓	✓	✓	Industry 5.0/ 4.0, AR/VR, Sustainability	✓	-
E12	Chartered Engineer/ Academic Researcher	✓	✓	✓	Industry 5.0/ 4.0, BC, Sustainability	✓	✓
E13	Academic Researcher/ Structural Engineer	✓	✓	✓	Industry 5.0/ 4.0, ML, IoT, Data Visualization, Sustainability	✓	✓
E14	Academic Researcher/ Facilities Manager	✓	✓	✓	Industry 4.0, AI, BIM, Construction Automation, Sustainability	✓	-
Total						14	11
Round 1		Phase I	Identify key elements of Industry 5.0.				
		Phase II	Identify enabling technologies which can be used with Industry 5.0				
		Phase III	Identify how to use enabling technologies with Industry 5.0 to align with sustainability in the construction industry				
Round 2		Phase I	Investigate the enabling technologies which can be used with each element of Industry 5.0 to align with sustainability in the construction industry				
		Phase II	Investigate how to use the enabling technologies with each element of Industry 5.0 to align with sustainability in the construction industry				

Delphi panel sizes should vary based on the topic, diversity of viewpoints, and available resources (Habibi et al., 2014). Delphi studies do not require large participant numbers for validity, with the recommended panel size typically ranging from 10 to 18 participants (Gray, 2016). Additionally, Skulmoski et al. (2007) suggest that a sample of 10 to 15 individuals may yield adequate and reliable results. However, the number of experts participating in each round can vary as participants may drop out or skip rounds (Avella, 2016). In this study, 14 experts participated in the first round, while 11 participated in the second, due to time constraints and data saturation. Data analysis was conducted using manual content analysis, a widely

used method for interpreting qualitative data from interviews, particularly when statistical analysis is not feasible (Bengtsson, 2016). Findings with a 75% agreement rate were accepted as the cut-off point, following similar previous studies (Moragane et al., 2024). At the end of each round, a summary of the findings from the preceding round was presented to the participants to obtain necessary feedback or comments if required.

4. Findings

The key empirical findings, validated through two rounds of semi-structured Delphi expert interviews, are discussed in this section in alignment with the research objectives.

4.1. KEY ELEMENTS OF INDUSTRY 5.0 (ROUND 1 PHASE I)

Key elements of Industry 5.0 identified in the literature were reviewed and validated in Delphi Round 1 Phase I to evaluate their applicability in the construction industry. According to the literature findings, Industry 5.0 encompasses three key elements, as shown in Table 1. Based on the responses, it was confirmed that these three elements: human-centricity, sustainability, and resilience, are indeed applicable to the construction sector. All the participants agreed with the literature findings and accepted 'human centricity', 'sustainability', and 'resilience' as the key elements of Industry 5.0. At the end of Round 1 Phase I, finalised elements were carried out for Delphi Round 2 for integration with enabling technologies.

4.2. ENABLING TECHNOLOGIES FOR EACH ELEMENT OF INDUSTRY 5.0 TO ALIGN WITH SUSTAINABILITY (ROUND 1 PHASE I, ROUND 1 PHASE II, ROUND 1 PHASE III, ROUND 2 PHASE I)

In the literature, nine enabling technologies of Industry 5.0 were identified. From Delphi Round 1 Phase II, eight technologies were deemed most applicable to the construction industry, with strong consensus on the transformative potential. These included seven technologies identified in the literature: AI, DT, Cobots, Big Data, BC, XR and additionally, BIM was added to the list with experts' agreement. However, EC and 6G technologies were excluded due to lower response rates (less than 75%), indicating the need for further awareness and understanding of their applications. In Delphi Round 1 Phase III, the focus was on investigating the use of these technologies with Industry 5.0 to enhance sustainability in the construction industry. Finally, at the end of this round, enabling technologies with 75% or more response rate were considered in Delphi Round 2 for integration with each Industry 5.0 element. During the Delphi Round 2 Phase I, the enabling technologies that are most applicable to each element were selected. Table 3 summarises the responses obtained corresponding to each Industry 5.0 element.

Table 3: Applicable enabling technologies for each Industry 5.0 element after Delphi Round 1

Industry 5.0 Elements	Applicable Enabling Technologies	No of Respondents
Human-centricity	Collaborative Robots	13
	Internet of Everything	13
	AI	12
	Digital Twins	11
	Big Data	11
Sustainability	Internet of Everything	13
	AI	12
	Blockchain	12
	Digital Twins	11
	Big Data	11
Resilience	AI	12
	Digital Twins	12
	Internet of Everything	11
	Big Data	11

As per Table 3, the majority agreed that Cobots would be the best technology to integrate with the 'human-centricity' element in the construction. However, E02 stated that "the human-centric element is mainly achieved through IoE and AI. So those are the two major technologies pushing this human-centric nature". According to E04's point of view, "DT, IoE, and Cobots are fundamental enable technologies for human centricity". Regarding the sustainability element, the consensus favoured IoE and AI as the most applicable enabling technologies. Likewise, for the resilience element, AI and DT were identified as most applicable. Meanwhile, E04, E05, E08, and E14 highlighted that the enabling technologies of Industry 5.0 are from Industry 4.0 era and are now being leveraged into Industry 5.0. E05 stressed, that the "most interesting focus of Industry 5.0 is on AI". Meanwhile, there is growing recognition of the potential offered by emerging technologies like DT, Big Data, and BC. E14 stated that "DT plays a big role in terms of infrastructure management and asset management". Further, E06 described about the integration of DT with Robotics to automate maintenance tasks in road development projects. The application of technologies to each element of Industry 5.0 was thoroughly explored during the second phase of Delphi Round 2.

4.3. APPLICATIONS OF ENABLING TECHNOLOGIES WITH EACH INDUSTRY 5.0 ELEMENT TO ALIGN WITH SUSTAINABILITY IN CONSTRUCTION (ROUND 1 PHASE III, ROUND 2 PHASE I, ROUND 2 PHASE II)

In Delphi Round 1 Phase III, the general use of enabling technologies with Industry 5.0 was explored. After that, the most applicable enabling technologies for each element were identified in Round 2 Phase I. Finally, an in-depth investigation was conducted in Phase II of Delphi Round 2, to examine how enabling technologies could be integrated with each element of Industry 5.0 to align with sustainability in the construction industry. The findings are summarised in Table 4.

Table 4: Integration of enabling technologies with Industry 5.0 elements after Delphi Round 2

Elements of Industry 5.0	Enabling Technologies	Use of Enabling Technology (Response rate ≤ 75)
Human-centricity	Collaborative Robots	Integrate Cobots for repetitive and hazardous tasks, allowing human workers for value-added activities.
	Internet of Everything	Leverage IoE for enhanced communication, coordination and decision-making in construction.
		Deploy IoE sensors for real-time monitoring, ensuring worker well-being and safety.
	AI	Use AI to analyse worker performance for personalised skill development plans, promoting transparency.
	Digital Twins	Create digital twins of construction sites to simulate and optimise workflows, enabling better planning and minimising risks.
	Big Data	Analyse big data to identify safety patterns and implement preventive measures.
Employ big data analytics for real-time monitoring of site performance, enabling data-driven decision-making.		
Sustainability	Internet of Everything	Utilise IoE to monitor and optimise resource utilisation, energy consumption, and waste management.
	AI	Apply AI for energy consumption modelling and optimisation in construction, ensuring sustainability.
	Big Data	Utilise big data analytics to track environmental impact throughout the construction lifecycle.
	Blockchain	Implement blockchain for transparent and traceable supply chain management
	Digital Twins	Use digital twins to simulate building life cycles and identify energy-efficient practices.
Resilience	AI	Implement AI for predictive analytics to identify risks and disruptions in construction projects.
	Digital Twins	Use digital twins to enhance project resilience by identifying vulnerabilities and developing contingency plans.
	Internet of Everything	Leverage IoE for real-time monitoring of construction sites, enabling quick response to disruptions.
	Big Data	Apply big data analytics for continuous monitoring of project performance and identifying early warning signs.

Regarding the integration of Cobots with human-centricity elements, E14 mentioned that “Robotics is a good example which can be used to perform tasks which are not safe for the humans. Also, the use of robots increases efficiency compared to labour”. E07 and E13 also provided supportive comments in this regard. Moreover, E01 provided an example for that as, “using a robotic dog with 3D cameras to check progress on construction sites,” where the dog is programmed to walk around the building and check progress. Concerning human-machine collaboration, E08 used the term “HCI” called “Human-Computer Interaction”. It was further elaborated as, “Integrating robotics into construction project management allows them to work alongside humans. While robots lack decision-making abilities, humans play a crucial role in guiding and aiding the decision-making process”. Further, E11 stated that “using AI, computer vision, ML, and deep learning for progress monitoring purposes avoids the subjectivity of humans and human errors. Also, it increases the efficiency”. Additionally, E10 stated that, “AI aids building certifiers by examining tricky areas, generating reports focusing on identified defects. This reduces their workload by 5-10%, enhancing efficiency via human-machine collaboration”. In considering IoE, E03 mentioned that “IoE serves as a means to seamlessly connect various systems and devices, facilitating easy and effective communication between people and machines”. Meanwhile, E06 emphasised that “while some argue that robots and AI can replace humans, I believe they can be used to enhance human capabilities in construction projects because ultimately human intelligence matters”.

The general view on the integration of IoE and sustainability was that we can use IoE to monitor and optimise resource utilisation, energy consumption, and waste management. Concerning AI integration with sustainability, it can be applied for energy consumption modelling and optimisation in construction. With IoE and AI the most common example used by E02, E06, E10, and E12, was the ‘smart building concept’ for energy efficiency. E12 explained it as “with IoE definitely a lot of things can be done in the energy efficiency area, particularly through improved iterations of the smart home concept”. Moreover, E06 detailed that “for example, utilising IoE and AI, we can establish benchmarks for systems like air conditioners, lighting, and heating. Then automated responses are triggered when conditions deviate, eliminating the need for manual intervention”. Focusing on maintaining a sustainable supply chain in the construction industry, the majority including E03, E08, and E11, suggested implementing BC for transparent and traceable supply chain management. According to E03, “BC

is essential for sustainable supply chain networks to improve transparency and accountability. It ensures a traceable and ethical flow of goods, contributing to a more sustainable and responsible supply chain". In addition, DT also can be used to enhance sustainability. It can be used to simulate building life cycles by identifying energy-efficient practices. E10 declared that "DT improves resource efficiency, productivity, and quality in construction projects. Even before construction, its 3D model with sensors helps to enhance design accuracy, optimise material usage and contributes to overall project efficiency". More to the point, E01 added that, "with DT, since everything is decided before the construction, you can see what sort of materials you can use, are they sustainable, and what are the alternative options you have".

Considering the resilience element, AI can be implemented for predictive analytics to identify risks and disruptions in construction projects. For instance, E13 stated that "AI capabilities can predict future project risks by analysing progress updates. This allows for better project planning, enhancing overall project management effectiveness". The applicability of DT is to enhance project resilience by identifying vulnerabilities and developing contingency plans. E07 stated that, "in terms of risk plans and prevention techniques, I think DT would be a good enabler because with that you can actually see what is going to happen during the construction beforehand". Hence it allows proactive identification of potential issues, enhancing the ability to mitigate risks before they occur. In addition, the IoE can be used for real-time monitoring of construction sites, enabling quick response to disruptions. Likewise, information integration for resilience can benefit from the IoE. E11 stated that "combining diverse elements and utilising stored information strategically enhances adaptability and resilience, making IoE a valuable tool in managing complex systems". Moreover, Big Data can support resilience for continuous monitoring of project performance and identifying early warning signs.

5. Discussion

Implementing Industry 5.0 in the construction sector will accelerate its transition into an environmentally sustainable, socially responsible, and economically prosperous industry (Tunji-Olayeni et al., 2024). However, within the construction industry, Industry 5.0 adoption remains limited as it is still transitioning towards Industry 4.0. Industry 5.0 diverges from Industry 4.0 by integrating humans and autonomous robots, resulting in a more efficient, meaningful production process (Ikudayisi et al., 2023). The literature identifies three key elements of Industry 5.0: human-centricity, sustainability, and resilience (Atif, 2023; Breque et al., 2021), which experts confirm as applicable to the construction industry. Moreover, nine enabling technologies for Industry 5.0 have been identified in the literature, with experts shortlisting seven of them as more applicable to the construction industry: AI (Pereira & Santos, 2023), IoE (Maddikunta et al., 2022), Cobots (Mahiri et al., 2023), DT (Mourtzis et al., 2022), Big Data (Leng et al., 2022), BC (Musarat et al., 2023), and XR (Xu et al., 2021). Additionally, experts acknowledged BIM as an important enabling technology for the construction industry as its expanding dimensions, have a greater potential to contribute to technological advancements in the construction industry.

This study explores the integration potentials of these enabling technologies with the key elements of Industry 5.0 to align with sustainability in construction. Findings emphasise the high applicability of AI, IoE, DT, and Big Data technologies with all three elements of Industry 5.0. Significantly, AI emerges as a common technology which enables the integration with all elements, facilitating analysis, optimisation, and decision-making processes. Moreover, Cobots exhibit a greater capacity for integration with the human-centricity element. E04 stated that "DT, IoE and Cobots are fundamental enable technologies for the human centrality". Additionally, E02, E06, E10, and E12 highlighted about achieving energy efficiency through the implementation of the 'smart building concept' utilising AI and IoE technologies. A recent study by Tunji-Olayeni et al. (2024) focuses on the application of technologies with Industry 5.0 which emphasises the applicability of AI with sustainability and resilience elements, but not with human-centricity element. However, it supports the applications of Cobots with human-centricity, and Big Data and BC with sustainability and resilience elements. Big Data can help the construction industry to understand construction patterns, building practice trends, and project abnormalities, while DT merges virtual and physical worlds to track construction progress accurately (Almusaed et al., 2023). Thus, both the literature and empirical findings suggest a high integration capability of enabling technologies with Industry 5.0 in the construction industry. However, the construction industry's adoption of these technologies faces multiple challenges such as high implementation costs, limited digital infrastructure, and resistance to change among workers. Overcoming these challenges will be essential for achieving the full potential of Industry 5.0, especially in resource-constrained and emerging economies. Additionally, continuous assessment of the impact of these technologies on construction sustainability will be crucial to ensure that Industry 5.0 genuinely contributes to environmental, social, and economic progress.

6. Conclusions

This study aims to investigate how to use enabling technologies with Industry 5.0 to align with sustainability in the construction industry. Through a critical literature review and two Delphi study rounds, it was confirmed that human-centricity, sustainability, and resilience are the key elements of Industry 5.0 applicable to construction. Eight enabling technologies were identified as most relevant: AI, IoE, Cobots, DT, Big Data BC, XR, and BIM. This study found that integrating these technologies with Industry 5.0 elements can significantly enhance productivity, safety, and sustainability in construction. For the human-centricity element, Cobots, IoE, AI, DT, and Big Data are most relevant. For the sustainability element, IoE, AI, BC, DT, and Big Data are key, while for the resilience element, AI, DT, IoE, and Big Data are crucial. The

findings emphasise the importance of technology-driven innovation for aligning construction practices with Industry 5.0. By strategically leveraging these technologies, construction companies can address key challenges, improve operational efficiency, and meet evolving market demands while contributing to sustainable construction. Recommendations suggest that the construction industry should strategically leverage these enabling technologies to enhance communication, real-time monitoring, and decision-making processes on construction sites. By embracing these technologies, construction companies can move toward a more sustainable, resilient, and people-focused industry. The study therefore sets a foundation for further exploration into practical strategies for implementing Industry 5.0 in construction, ultimately contributing to the sector's long-term advancement in sustainability and innovation.

6.1. IMPACT TO THE INDUSTRY, RESEARCH, AND SOCIETY

This study facilitates the construction industry's transition to Industry 5.0 by identifying key technologies and providing actionable strategies to enhance productivity, safety, and environmental performance. It offers theoretical insights into the sustainable adoption of enabling technologies, thus enriching the body of knowledge on how technological advancements influence industrial practices. Additionally, this study addresses societal concerns by promoting sustainability and human well-being, thereby contributing to the development of a better society without compromising technological advancements.

6.2. FURTHER STUDIES

Future research can be directed towards investigating the applications of technologies associated with Industry 6.0 to enhance sustainability in the construction industry. This includes identifying key elements and enabling technologies of the sixth industrial revolution and examining how they can be utilised to promote sustainability in construction practices.

6.3. LIMITATIONS OF THE STUDY

The study is focused on enabling technologies and their integration with Industry 5.0 elements and it might overlook other external factors, such as regulatory and economic barriers, that could influence the adoption of these technologies in construction.

7. References

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