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Review

Applications of Intelligent Models in Processes in the Construction Industry: Systematic Literature Review

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Abstract

There is a growing role of AI and intelligent systems in construction efficiency, safety, and decision-making. Reviewing existing applications helps guide future innovation, informs industry practices, and supports sustainable development. This paper discusses how advanced technologies in the construction industry such as Industry 4.0, IoT, and 3D printing are transforming the construction industry. The main objective is to explore how these tools are being used, what benefits these applications offer, what challenges companies face when adopting them, and what steps can make the transition easier. To do this, a structured review of 115 recent studies published between 2015 and 2025 was carried out by utilizing authentic databases such as Scopus, Web of Science, and ScienceDirect. The research shows that these technologies can make construction faster, safer, and more sustainable, but adoption is still held back by high upfront costs, a lack of digital skills, and unclear regulations. These issues are especially tough for smaller companies and those in developing regions. The paper offers practical recommendations for both researchers and practitioners to help bridge the gap between potential and practice and support a smarter, more efficient future for construction.

Keywords: construction industry; IoT; Industry 4.0; digitalization; 3D printing; sustainability; smart technologies

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1. Introduction

In the past few years, the construction industry has been developing and advancing towards using smart technologies together with digital innovations, which improve efficiency, abilities, project management, decision-making, and automation of the processes [1,2]. Smart technologies are intelligent systems that can help in providing real-time data by capturing and analyzing the data to help in the different construction processes [3,4]. These technologies can help in mitigating the delays in projects, maintaining the overall cost, and enhancing the quality of the project [5]. Artificial intelligence (AI), Internet of Things (IoT), Building Information Modelling (BIM), robotics, blockchain, and 3D printing are examples of these technologies [6,7].

Based on [8,9], smart technologies can help transform the traditional construction industry processes into more enhanced, developed, and sustainable processes. It was

mentioned by [10,11] that these technologies can reduce the operational cost, improve decision-making, and improve work quality. Additionally, they can enhance user experience, provide longer life span of construction buildings, and reduce the number of laborers [12,13]. In this study, the main focus is to address the smart technologies of Industry 4.0.

The analysis for this study is based on the main topics, Industry 4.0, Digitalization/IoT, and Additive Technologies (3D printing). These topics were reviewed because they were highlighted the most in the 115 reviewed literature. Some of the reviewed technologies in this study are not considered as standalone technologies; instead, they are mentioned as an enabler or supporting technology for one of the three main topics. For instance, AI and robotics are considered enablers for Industry 4.0. Recent studies in AI and machine learning are supporting the context of this study. As an illustration, machine learning was used by [14] to enhance the cutting quality of a CO_2 laser in FFF printed polymers. On the other hand, [15] used MIMO neural networks for modeling sand-mold systems. These recent studies highlight that AI and machine learning can be used for a broader perspective; however, this study aims to focus on the construction industry. Unlike earlier reviews that focused narrowly or remained conceptual, this study fills the gap with a broad, quantified synthesis across multiple domains. With this framing, our study addresses the following research questions (RQs):

- RQ1: What are the technologies of Industry 4.0 that were used in the construction industry?
- RQ2: What are the benefits and advantages of using these technologies?
- RQ3: What are the obstacles that slow down the adoption of these technologies?
- RQ4: What research gaps and future directions are identified in the existing literature?

Industry 4.0 is called the fourth industrial revolution [14]. It helps transform the construction industry into more interconnected digital systems that rely more on automation and cyber systems [15,16]. This transformation will help increase the productivity and efficiency of construction processes and sustainability of the construction structures [17,18]. Citing [19,20], Industry 4.0 enhances the project management practices in the construction industry. This usually leads to customer satisfaction by making the project proactive in all aspects [21].

Traditional construction is facing a lot of challenges, such as project delays, cost overruns, low-quality work, lower customer satisfaction, and poor process management. Traditional construction, as mentioned by [22], is causing more greenhouse gas emissions as it consumes a lot of energy, which is bad for the environment. Traditional construction is suffering from unskilled laborers, higher numbers of worker turnover, and a lot of safety issues [23]. It was stated by [24] that the construction industry is known for low-quality work and bad planning practices. Citing [25,26], the traditional procurement system used in the construction industry is causing a lot of project delays, low performance practices, and cost overruns. This usually happened due to inadequate training, lack of communication, rework, and bad planning and management systems.

Bad safety management systems are also one of the challenges in the construction industry, as stated by [27]. The number of accidents and safety issues is high compared to other industries. All these challenges are highlighting the need for relying on the new digital technologies, which have proved their effectiveness in mitigating project delays, maintaining project cost, increasing productivity, improving safety practices, and reducing construction waste.

Several construction projects were performed globally and highlighted the impact of intelligent technologies. For instance, the Huzhou Qilitang project is one of the projects that was performed by using IoT and BIM to enhance the project management, which resulted in improved coordination between all departments, higher efficiency for all the

activities, and enhanced project outcomes [28]. Similarly, according to [29], the Office of the Future in Dubai was built using 3D printing technology, which reduced the time needed to finish the project, less overall cost, enhanced material usage, and less material waste. These case studies clearly show that emerging technologies can be used to overcome the current obstacles facing the construction industry and lead to sustainability, higher efficiency, and planned cost maintenance. By looking at these projects through the lens of Industry 4.0, this study highlights how digital technologies like IoT, BIM, and 3D printing are changing the way construction is carried out globally, providing new insights into their transformative role.

Importance of Digital Technologies

The requirements of the construction industry have significantly increased. Customers and stakeholders are looking for efficient, sustainable projects that can be carried out in limited time using a lower budget and at the same time maintaining higher safety measures. It was reported that [30,31] efficiency in construction is referred to as increasing productivity, meeting project deadlines, improving planned stages, and reducing materials waste. Sustainability is considered to be the ability to change the practices that pollute the environment, as stated by [32,33], such as the practices that cause greenhouse gas emissions and increase construction waste. Safety measures are also one of the main priorities for the construction industry [34]. It needs the discipline and commitment of construction companies to mitigate accidents in construction sites and protect laborers. All these requirements cannot be achieved through traditional construction, which relies on manual laborers.

Digital technologies are the solution for most of the issues that face the construction industry by providing real-time data, connecting all the processes, analyzing the data, and becoming proactive. By way of example, the implementation of BIM improves the efficiency of the processes as it connects all the processes digitally, which enables different parties to cooperate [35]. This cooperation will lead to more accuracy for cost and time estimation and will reduce the potential issues or mistakes that might arise in the future [36].

In like manner, IoT is improving the effectiveness of the construction processes, as mentioned by [37], by enhancing their efficiency with high safety measures. The sensors and smart devices that can be used by IoT will provide real-time data that helps mitigate risks or prevent them. These sensors collect data about robotics and the health conditions of the workers. In accordance with [38], who stated that these data can be used to increase the productivity of the workers and improve their efficiency. For instance, IoT can be used as a predictive maintenance tool, which can monitor the tools and equipment for the purpose of detecting any malfunction or issue with the equipment so it can be fixed [39].

As far as sustainability is concerned, additive manufacturing (3D printing) has proven to be a good tool for reducing construction material waste by improving the way of using materials. Construction projects that use 3D printing have proven their sustainability for the environment. As an illustration, Dubai's Office of the Future achieved a low construction waste rate and low greenhouse gas emissions [40]. Additionally, blockchain technology enhances the supply chain management process through tracing the construction materials for the whole project life cycle. This technology will give companies, as stated by [41], the ability to be sustainable economically and environmentally by preventing fraud, mitigating conflicts, and managing logistics effectively. Thus, smart technologies are the solution to the issues that face the construction industry.

Building on the transformative power of intelligent technologies in construction, this research takes a close look at existing literature to bridge the gap between theory and real-world practice. By exploring current applications, uncovering common hurdles to

adoption, and offering practical strategies, it aims to help industry professionals confidently navigate and embrace the shift toward digital transformation.

2. Methodology

To obtain a clear picture of how technologies of Industry 4.0 are transforming the construction industry, this study followed a structured yet practical literature review. The aim was to gather recent, high-quality research focusing on digital technologies such as IoT and 3D printing in construction settings. These three core areas, Industry 4.0, IoT, and 3D printing, were chosen because they are among the most influential drivers of digital transformation in construction, addressing automation, real-time data exchange, and additive manufacturing.

Literature was primarily gathered from Scopus (Elsevier B.V., Amsterdam, Netherlands) and Web of Science (Clarivate Analytics, Philadelphia, PA, USA), both recognized for their peer-reviewed, high-impact journals, ensuring that the selected works met rigorous academic standards. Google Scholar (Google LLC, Mountain View, CA, USA) and ScienceDirect (Elsevier B.V., Amsterdam, Netherlands) were also consulted to capture relevant studies that are not fully indexed in the former two databases. Searches were conducted using a combination of keywords such as Industry 4.0, construction 4.0, IoT, 3D printing, and construction industry, restricted to title, abstract, and keyword fields. Additional keywords like digitalization, smart technologies, and sustainability were used where needed, and publication dates were limited to works from 2015 to 2025.

To avoid selectivity, explicit inclusion and exclusion criteria were applied. Inclusion criteria required peer-reviewed publications that directly discussed Industry 4.0, IoT, or 3D printing in a construction context, published in English between 2015 and 2025, and preferably indexed in Scopus or Web of Science. Exclusion criteria ruled out non-academic materials, duplicate records, and articles whose focus was outside construction or lacking methodological clarity.

An initial search yielded over 175 articles. First, titles and abstracts were screened to remove any unrelated or clearly out-of-scope studies, leaving around 133 publications. Next, full texts of these articles were assessed in detail, eliminating those that did not meet the inclusion criteria or provided insufficient discussion of Industry 4.0, IoT, or 3D printing in the context of construction. Through this process, 115 relevant studies were finally selected for thorough review and analysis.

Key information extracted from each study included the publication year, journal or conference details, and the primary technology focus. Findings were categorized using a thematic analysis approach, grouping studies based on recurring topics such as project management, safety, sustainability, and cost-effectiveness. This systematic process helped synthesize scattered insights into a coherent review that directly addresses the paper's objectives. By clearly specifying databases, search strings, inclusion and exclusion criteria, and a stepwise screening process, the methodology ensures transparency and reproducibility, moving beyond any semblance of arbitrary selection.

In this study, the PRISMA 2020 guidelines have been followed. The initial number of studies that were identified is 175 studies. These studies were gathered through Scopus, Web of Science, ScienceDirect, and Google Scholar. These studies have been carefully checked and screened to remove any duplicates. This step resulted in the removal of 30 studies, as 23 of them were duplicates and 7 were considered irrelevant. The remaining 145 studies were screened by checking the title and the abstract, which resulted in excluding 26 more studies. The remaining studies were fully checked to assess whether they are eligible to be included in the study or not. This process led to excluding another 4 studies

due to methodological limitations or being irrelevant to Industry 4.0. Figure 1 illustrates the selection process.

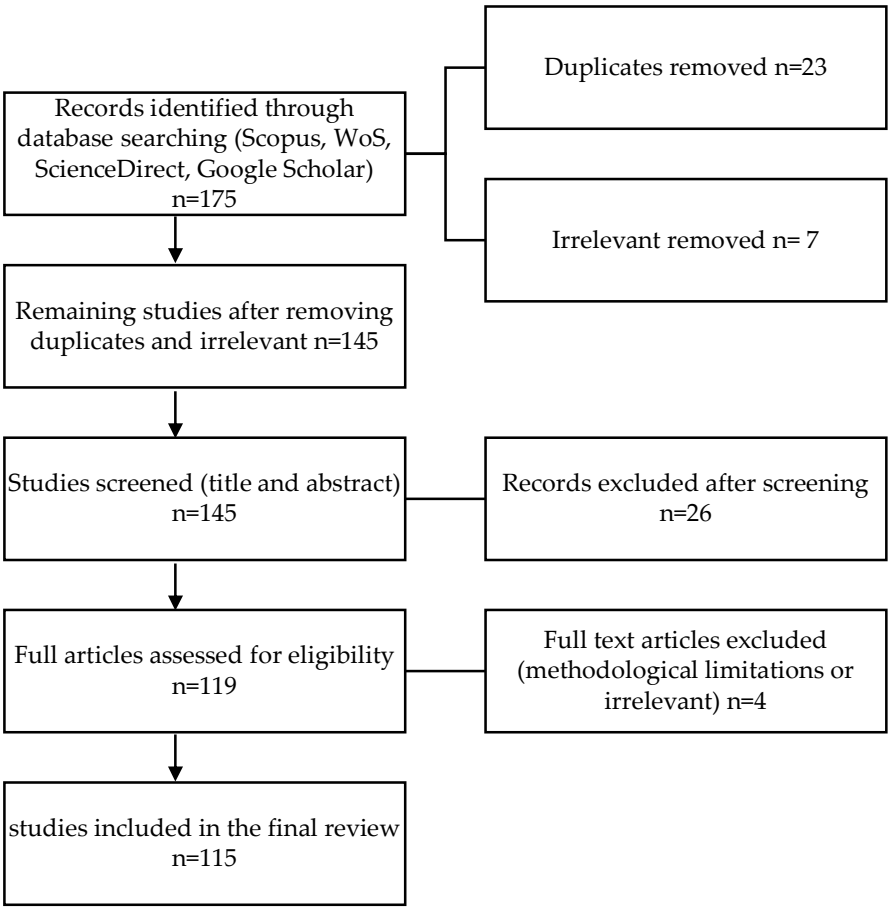


Figure 1. PRISMA 2020 flow diagram of the study selection process.

The selected literature also covered a wide geographical range, including research and case studies from Asia (e.g., China's Huzhou Qilitang Project, India, Malaysia, and Vietnam), the Middle East (e.g., UAE, Dubai's Office of the Future, and Saudi Arabia), Europe (e.g., UK and Switzerland), and North America (USA). This diversity highlights the movement towards Industry 4.0 applications in construction globally. It also allows for comparisons across different economic, cultural, and regulatory contexts.

3. Results

In this study, 115 studies that were published between 2015 and 2025 were reviewed. In this section, a summary of the three main findings of the previous literature on Industry 4.0 in Construction, Digitalization and IoT, and Additive Technologies (3D printing) will be discussed to answer all the research questions.

3.1. Industry 4.0 in Construction—Results Summary

The previous literature highlighted several technologies that Industry 4.0 includes, such as robotics and automation, which have been used to perform high-risk activities, ensuring the safety of the workers, and increasing productivity. AI and machine learning are another example of Industry 4.0 technology that have been used to gather real-time data and perform analytics that help in decision-making and risk management. Finally, the blockchain was used to improve the supply chain management and contract management. These technologies have made construction projects more efficient, safe environment

for workers, and improved supply chain management. There are several challenges that Industry 4.0 faces, such as the lack of a skilled workforce that can operate these technologies, high initial cost, and lack of regulations that support these technologies. Industry 4.0 still needs to be screened and monitored to better understand the long-term effects of sustainability, project cost, and workforce productivity.

3.2. Digitalization and Internet of Things (IoT)—Results Summary

Digitalization was highlighted a lot in the previous literature, especially with Building Information Modelling (BIM) and the Internet of Things (IoT). For instance, BIM was used in the beginning stages of the construction project as a tool that helps to estimate the overall cost, schedule, activities, and improve the project management collaboration. On the other hand, IoT has a lot of applications that were reported in the literature, such as sensors, RFID technologies, and wearables. These applications help in monitoring all equipment around the construction site, checking the environmental conditions to alert for any hazards, and regularly checking the health conditions of workers. The use of digitalization and IoT has enhanced the safety of the workers around the construction site, helped in maintaining the equipment and machines by using predictive maintenance, and maintained the overall planned budget and schedule. These technologies are facing a lot of challenges that need to be addressed, such as potential cybersecurity threats, difficulties managing the data, and limited interoperability among IoT systems. The research gaps that were identified are lack of integration between BIM and IoT in one platform, privacy concerns of the workforce because of collecting data from them, and expanding these applications in several regions around the world to check their impacts.

3.3. Additive Technologies (3D Printing)—Results Summary

Additive manufacturing (3D printing) was highlighted in the literature as the focus is becoming more on this technology. It was already used in Dubai's Office of the Future project, which showed that it is a technology that is capable of using materials efficiently and will shorten the time needed to finish the project. The main benefits that were highlighted are sustainability, less material waste, and maintaining the overall cost. Three-dimensional printing is still facing some obstacles, such as uncertainty regarding the existence of a clear building code, high initial cost, and lack of a skilled workforce. Research gaps were identified for this by mainstream adoption to other regions and developing countries, and having clear standard quality and safety building codes.

3.4. Summary of Findings

Table 1 is a summary of the weight of each technology from the 115 studies, the benefits, and the main challenges.

Table 1. Summary of findings.

Technology/Theme	(%) of Studies	Key Benefits	Main Challenges
Robotics and Automation (Industry 4.0)	13	Performs repetitive/high-risk tasks; improves safety and productivity	High cost of adoption, workforce adaptation, and technical limits
AI and Machine Learning (Industry 4.0)	17.5	Predictive analytics, risk management, automated decision support	Data availability, skilled workforce shortage, and model generalization
Blockchain (Industry 4.0)	8.75	Transparency in supply chains, smart contracts, and trust in data	Lack of regulation, interoperability issues, and adoption reluctance

Table 1. *Cont.*

Technology/Theme	(%) of Studies	Key Benefits	Main Challenges
BIM (Digitalization)	22.75	Collaboration, cost/time accuracy, and digital project management	Interoperability, training requirements, and resistance to adoption
IoT (Digitalization)	26	Real-time monitoring, predictive maintenance, safety tracking	Cybersecurity risks, data overload, privacy issues, and integration challenges
3D Printing (Additive Technologies)	13	Sustainability, reduced waste, faster project delivery, and innovative designs	High equipment cost, regulatory gaps, lack of skilled operators

As shown in Figure 2, digitalization and IoT are the most highlighted among the reviewed 115 studies, with 48.75%, followed by Industry 4.0 with 39.25%, followed lastly by 3D printing with 13%.

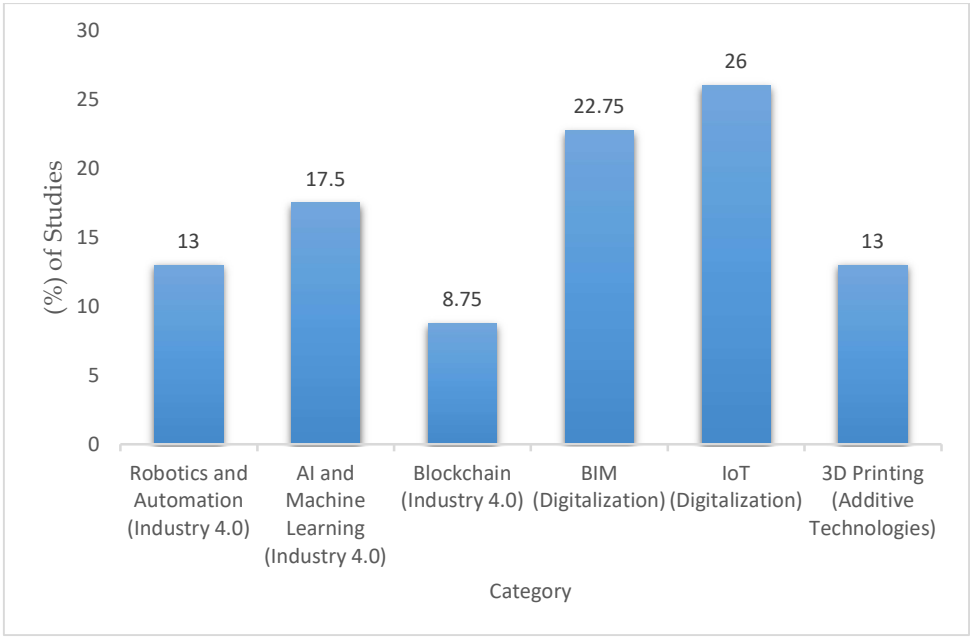


Figure 2. Distribution of studies by technology across 115 reviewed articles.

Table 2 highlights how IoT, BIM, and 3D printing differ in their impact, costs, adoption, and maturity. (Typical time to value) describes how long it usually takes after adopting a technology before its benefits can be clearly seen in practice, based on evidence from the reviewed studies.

Table 2. Comparative synthesis across technologies (IoT, BIM, and 3D printing).

Technology	Primary Impact Areas	Impact Level	Cost Profile	Adoption Level	Maturity/ Readiness	Typical Time to Value	Common Barriers	% of 115
IoT (Digitalization)	Real-time monitoring, safety, asset tracking, predictive maintenance, and site logistics	High	Moderate CAPEX (sensors, gateways); OPEX for connectivity/cloud	High (widely piloted and scaled on sites)	High (proven building blocks; integration still needed)	Short (weeks, months once instrumentation is deployed)	Cybersecurity, privacy, data overload, and change management	26

Table 2. *Cont.*

Technology	Primary Impact Areas	Impact Level	Cost Profile	Adoption Level	Maturity/ Readiness	Typical Time to Value	Common Barriers	% of 115
BIM (Digitalization)	Design coordination; planning; cost and schedule control; collaboration	High	Moderate High CAPEX (licenses); training/time investment; integration services	High (standard practice in many regions/projects)	High (mature platforms and workflows)	Short Medium (benefits realized after model setup and team onboarding)	Interoperability across tools; skill gaps; resistance to process change	22.75
3D Printing (Additive)	Rapid prototyping; on-site/off-site printed elements; efficiency; waste reduction	Moderate High	High CAPEX (printers, materials); specialized expertise; certification/QA costs	Low Moderate (limited large-scale deployments)	Medium (emerging standards; maturing hardware/ processes)	Medium Long (pilot-to-scale transition needed; permitting/ codes)	Codes/standards immaturity; high upfront cost; operator skills; supply chain	13

4. Industry 4.0 in Construction: An Overview

4.1. Definition and Core Principles

The term Industry 4.0 refers to the fourth industrial revolution, which provided smart technologies that can be connected. These technologies are AI, automated systems, IoT, and big data. When Industry 4.0 was implemented in the construction industry, it was called construction 4.0, and it was used to digitalize and automate the construction industry. It was reported by [42] that construction 4.0 is used to connect all the processes in the construction site and digitize it throughout the whole project life cycle. Construction 4.0 does not have a specific definition; however, its features are known to provide process connectivity for construction projects, which helps in decision-making based on the analysis and statistics [43]. Based on [44], the integration of Industry 4.0 technologies will enhance the outcome of the construction project. Citing [45,46], the complexity of the construction industry and the resistance to change have slowed down the implementation of Industry 4.0 in the construction industry.

Industry 4.0 has its own core principles, which were tailored to be used in the manufacturing industry; however, it can still be used in the construction industry. These principles are modularity, decentralization, real-time capability, virtualization, and Integration and Interoperability. Modularity refers to the flexibility of the construction project through adding or removing any tool or machine without affecting the project. For instance, in design, the project should be flexible to any change or requirement without delaying the project or increasing its cost [47].

Decentralization gives the employee on the construction site the ability to make decisions based on real-time data [48]. This can help in optimizing the construction processes. According to [49], decentralization helps reach a quicker decision, which is based on real-time data without the need for centralization or hierarchical decision-making. Interoperability is another principle for Industry 4.0, which integrates different systems together for enhanced communication between stakeholders and devices [50]. Interoperability enhances decision-making, as mentioned by [51], by providing information about the different stages of the construction project. All these principles provide a connected Industry 4.0 system which enhances the overall performance of the project [52].

4.2. Industry 4.0 in Construction—Benefits

Construction 4.0 proved to be a useful tool for improving the safety of the workers during the project life cycle [53]. According to [54], construction 4.0 can be used alongside different sensors and wearable devices, which can detect the health conditions of the workers and assess the situation of the construction site. This will help to mitigate accidents on the construction site by giving the ability to respond to any health issue or accident that

might happen. A case study was conducted in Malaysia by [55], who managed to highlight that construction 4.0 is the solution to improve the safety in the construction sites and mitigate the accidents by having an efficient risk management system. It was found that integrating BIM is a huge boost to improving the health and safety of the construction site.

Construction 4.0 is a useful tool for efficient project management as it uses analytics tools and provides transparency for the data, which eventually leads to better decision-making [56]. Looking at a concrete example, a bibliometric study and literature review were conducted by [57], who managed to identify that the integration of construction 4.0, such as AI and robotics, enhances the overall performance of the project and reduces resource waste. Citing [58], construction 4.0 can improve efficiency by better utilization of materials, which leads to less project time and cost. A case study was conducted by [59] in the United Arab Emirates to determine the benefits of construction 4.0, and it was found that construction 4.0 is environmentally sustainable because of reduction in construction waste. It was reported that construction 4.0 is economically and socially sustainable as it will maintain the cost and provide better health and safety measures.

4.3. Industry 4.0 in Construction—Challenges

Although construction 4.0 has a lot of benefits, it faces a lot of challenges that slow down its adoption in the construction industry. One of the main challenges, as stated by [60,61], is the high initial cost for implementing construction 4.0. This high initial cost can be very difficult, especially for small to medium construction companies, as they will have to invest in drones, sensors, and 3D printing. In a related study, it was stated by [62] that the high initial cost will include providing adequate training for the workers to be able to operate the new technologies. These new technologies will require maintenance, which adds additional high initial cost for construction 4.0 [63].

Lack of skilled staff is another challenge for the adoption of construction 4.0 [64]. The staff should have the skills that enable them to operate these new technologies and, at the same time, learn new skills to adapt to the rapidly changing technology [65,66]. According to [67], the current workforce does not have the required IT skills to make them able to handle construction 4.0. In a related study that was performed in Malaysia, it was reported by [68] that a lot of workers do not have any skills with computers, which makes it difficult to teach them how to handle the new technologies.

Resistance to change that arises from the workforce is another challenge that faces the adoption of construction 4.0 in many countries [69]. By the authority of [44], the resistance to change mostly will happen because the worker will fear losing his job because of these technologies, or because he is used to the traditional construction and refuses to learn new skills. Lack of regulations and standards is another obstacle in the way of adopting construction 4.0, as it will lead to uncertainty [62]. A case study was conducted in India by [70], who managed to identify a lack of skilled workers as one of the challenges in India. In Vietnam, high cost of construction and lack of long-term planning are some of the challenges for construction 4.0 adoption [71].

5. Digitalization and Internet of Things (IoT)

5.1. Digitalization in Construction

Digitalization in construction is about shifting traditional manual processes toward using digital tools to improve how teams gather, share, and analyze information [72,73]. It is seen through technologies like Building Information Modelling (BIM), digital management software, cloud collaboration platforms, and on-site sensors. These digital tools support the broader idea of Construction 4.0, helping project teams stay connected and make decisions based on accurate, real-time data. Instead of relying on printed drawings or

handwritten notes, teams now use digital models, dashboards, and mobile apps to manage changes, track progress, and communicate seamlessly. The main advantage is breaking down barriers between architects, engineers, contractors, and facility managers, so everyone works together smoothly with the latest information. Digitalization also lets teams visualize and simulate projects ahead of time, spotting potential issues early and refining plans before actual construction starts [74].

5.2. IoT Applications in Construction

The IoT can be integrated with a lot of equipment and tools, which can enhance the overall performance of the construction project [75]. For instance, IoT can be integrated with sensors or devices that can monitor the workers, machines, materials, and the environment. These devices can collect data from every machine, and they can be integrated into them so they can do analysis and provide real-time data. As an example, these sensors can help in scheduling the maintenance for machines without delaying the project. They can also determine the working hours so the machines can be used effectively and monitored. According to [76], IoT sensors can track construction equipment and machines around the construction site, which lets the managers know the location of the machine, reduce downtime, and perform predictive maintenance for machines. IoT sensors can detect the material quaintly so it can be used effectively and prevent theft [77].

IoT systems provide real-time data analysis, which allows the decision-making process to be automated [78]. In accordance with [79], workers are provided with wearable devices that are intended to use IoT to help assess the health and safety of workers. As an illustration, wearable devices can alert managers and staff when there is an injured worker. Furthermore, wearable devices can monitor the heart rate of workers so they can detect any worker who suffers from fatigue or any other health conditions. IoT sensors can help in detecting potential hazards by monitoring the dust levels, temperature, gas emission levels, humidity, CO_2 levels, and ventilation in closed areas [76]. By the authority of [80,81], IoT can be integrated with tools such as RFID to help monitor and track the progress of the project by helping managers to know when the delivery of the materials was made and when it was installed. This can help significantly in reducing project time by comparing the planned schedule with the actual work [81]. This process is happening automatically without the need for manual documentation, which reduces potential errors and allows for real-time data recording according to what was performed [82].

5.3. Digitalization and Internet of Things (IoT)—Benefits

IoT has many benefits in terms of cost, project timeline, safety measures, and quality. It can reduce costs by monitoring project progress, which helps staff avoid delays and prevents stakeholders from incurring additional expenses. Based on [83,84], Unmanned Aerial Vehicles (UAVs) are one of the IoT applications that improve project management by monitoring construction sites. IoT applications also reduce administrative costs by using software that enhances communication between stakeholders [85]. In the same study, reported that many projects adopting IoT significantly achieved strong returns on investment. Furthermore, IoT sensors and applications minimize machinery downtime, which lowers costs and increases productivity [86,87].

IoT gives the ability to make an immediate decision-making process supported by data analysis [88,89]. This will help in reducing the actual time needed to finish the project and avoid any delays [89]. It was stated by [90] that IoT can increase productivity of the construction work. IoT can be used to make the construction sites safer for staff, and it will greatly reduce accidents. Citing [91], IoT sensors can monitor the vital signs of workers to check whether they are in good health or not. It was mentioned that it can also detect

any potential accident that might occur. It can also provide alerts for any maintenance that needs to be performed for any machine, so no accident can happen from the failure of any machine. If the safety protocols are not followed, IoT sensors will detect them and will force the operation or the machine to stop until workers follow the safety procedures [92].

5.4. Digitalization and Internet of Things (IoT)—Challenges

While IoT offers a lot of benefits to the construction industry, several practical challenges must be carefully managed. Cybersecurity remains a major concern, as connecting construction sites to the internet exposes projects to risks like data breaches, unauthorized control over equipment, and potential safety threats [93]. Many construction firms lack dedicated cybersecurity expertise, increasing their vulnerability, especially if IoT devices are not regularly updated or properly secured [94,95]. Additionally, interoperability is problematic, with various proprietary IoT systems covering equipment, workforce, and environmental sensors often not integrating seamlessly into central management software [96]. Without common standards or compatible platforms, firms struggle to unlock IoT's full value [97].

Another critical challenge, as reported by [98], is handling the massive influx of data IoT devices generate. Based on [99], construction companies often find themselves overwhelmed, lacking sufficient analytical capabilities to translate this data into actionable insights. Without specialized skills or dedicated analytics teams, much of this valuable information goes unused. Based on [78], privacy also becomes an issue, especially when IoT devices like wearables track workers' movements or biometric data, raising concerns among employees and labor groups about intrusive surveillance. Moreover, despite declining sensor costs, the overall financial investment remains high, discouraging firms operating on slim margins from widely adopting IoT unless mandated or incentivized [76]. Overcoming these hurdles by investing in cybersecurity, analytics, interoperability solutions, and responsible privacy practices is essential for realizing IoT's promise of smarter, safer, and more efficient construction operations [100,101].

6. Additive Technologies (3D Printing)

6.1. Current Uses of 3D Printing in Construction

Additive manufacturing and 3D printing are making waves in the construction industry as a standout technology from the Industry 4.0 revolution [102]. This approach uses robots to layer construction materials precisely, building everything from structural components like walls to entire buildings [103]. For instance, concrete 3D printers have been used to create complex wall panels and load-bearing elements both on-site and in factory settings, as demonstrated by projects like Switzerland's DFAB House and various innovative structures in China. Companies like Apis Cor in Russia and ICON in the USA are also exploring the possibilities of 3D printing for quickly erecting small homes and affordable housing, highlighting the technology's potential to reduce the need for skilled labor and speed up construction.

Moreover, 3D printing is not just about building the big stuff; it is also perfect for crafting modular and prefabricated design elements that add a unique touch to any project [104,105]. This includes everything from intricately designed decorative panels to custom staircases that can be pre-made in a factory and simply assembled on-site. Citing [106], the technology even stretches into infrastructure, with projects like 3D printed concrete bridges and experiments in using 3D printing for rapid repairs, like fixing potholes. As 3D printing continues to evolve, it is becoming clear that it could soon be a routine part of building and design, offering solutions where traditional construction methods fall short in terms of labor and cost.

6.2. Additive Technologies (3D Printing)—Benefits

Additive manufacturing is transforming the construction world with its strong emphasis on sustainability [107]. Based on [108], this technology minimizes waste dramatically compared to traditional construction methods, which often involve excess materials like timber off-cuts and surplus concrete ending up in landfills. With 3D printing, each material is used precisely as needed, leaving virtually no waste behind. Additionally, this approach can incorporate recycled materials such as demolition waste into new projects, turning what would be trash into valuable resources and significantly boosting overall resource efficiency.

Beyond just reducing waste, 3D printing makes construction cleaner and more energy efficient [109]. By cutting down the need for extra materials like formwork and speeding up the building process, it reduces energy use and carbon emissions. Plus, it opens up new design possibilities that were once considered too challenging or expensive to achieve, such as intricate lattice structures that use less material without compromising strength. This not only helps in optimizing material use but also in crafting buildings that are better adapted to their environments, enhancing their energy efficiency over time. Additionally, with fewer workers and less machinery required on site, the typical disturbances of construction like noise and air pollution are greatly diminished [110,111]. This quieter, cleaner process not only benefits the planet but also supports a quicker, more cost-effective path to meeting housing needs, perfectly marrying environmental consciousness with economic and social benefits [112].

6.3. Additive Technologies (3D Printing)—Challenges

Despite its groundbreaking potential, 3D printing in construction has not hit the mainstream yet, and it is mainly due to a few substantial roadblocks. First up, the cost and complexity of that technology, as reported by [110], are significant hurdles. The printers needed are not just any printers; they are large, sophisticated machines that require a hefty upfront investment. Plus, they need specific conditions to operate effectively, especially when working with tricky materials like concrete that must cure just right to be structurally sound [113]. Even with these high-tech machines, there is still a need for human hands for tasks like adding reinforcement or finishing touches, which means the process is not fully automated yet.

Then there is the maze of regulatory challenges. Building codes that have been around for decades are tailored to traditional construction techniques, leaving 3D printed structures in a regulatory limbo without clear guidelines on key safety and quality standards [114]. This makes it tough to obtain the necessary approvals to move beyond experimental uses. On top of that, there is the workforce to consider. Shifting to 3D printing requires a different set of skills, as mentioned by [115], and not all construction teams have the expertise to handle these advanced machines. Plus, some in the industry are wary of the new technology, worried about job security as machines take on tasks once performed by hand. While 3D printing offers exciting advantages like drastically cutting down on waste and allowing for innovative designs, it is still mostly used for smaller or less critical parts of projects. As we tackle these challenges, the integration of 3D printing into construction might gradually increase, particularly in situations where traditional methods fall short.

7. Discussion

The main purpose of this study is to systematically review 115 previous studies on smart technologies in the construction industry. In this section, the findings are going to be discussed to show the agreement, differences, and the novelty of this study.

7.1. Consistency with Prior Research

The findings of this study are aligned with previous literature findings and support them. For instance, it was reported by [1,2] that BIM is being used and adopted globally in a lot of countries and regions due to it is ability to estimate the budget required for the project, improve the coordination and collaboration, and design different construction elements with high accuracy. On the other hand, IoT was also reported to be recognized and used globally due to high safety measures and real-time data that can be used for monitoring. In this study, it was observed that BIM and IoT are represented and reviewed by nearly half of the 115 reviewed studies, with 49% (Table 1, Figure 2). More benefits were identified in this study, such as improved efficiency, mitigation of the schedule delays, improved safety measures, and sustainability, which align with the reviewed literature such as [3]. This consistency ensures that the use and adoption of smart technologies in construction improve the overall performance and outcomes of projects.

7.2. Contrasts with Previous Studies

Industry 4.0 tools were highlighted in the previous literature as side topics, such as blockchain and robotics, while our study observed that there is a growing research interest in these technologies. As an illustration, blockchain is increasingly being used for supply chain management and smart contracts. Robotics is also being recognized more due to its ability to perform regular and high-risk activities. This suggests that the use of smart technologies in construction is not just about BIM and IoT, as it is also moving more widely towards Industry 4.0 technology. In this study, AI and machine learning were identified as emerging tools for Industry 4.0, especially for risk mitigation and prediction. Also, the analysis of this study observed that one fifth of the reviewed literature. To obtain more understanding about the reviewed literature and how it addresses these technologies, Table 3 presents a summary of representative works, organized by technology, region, and methodology.

Table 3. Summary of representative studies on Industry 4.0 technologies in construction by theme, region, and methodology.

Reference	Topic Focus	Research Method	Key Findings	Challenges/Limitations	Region	Research Gap
[44]	Industry 4.0	Triangulation (Literature Review + Industry Analysis)	Outlined implications of digitalization in construction; proposed framework for Construction 4.0.	Fragmentation, resistance to change, and lack of standards.	Global	Need for detailed practical implementation strategies for Construction 4.0.
[65]	Use of deep learning in construction	Review	Deep learning enhances automation and decision-making in construction.	Data scarcity and model generalization issues.	Global	Real-world implementation
[66]	Artificial intelligence in construction	review	Highlights growing potential of AI in automating tasks and enhancing efficiency	Data availability and lack of a skilled workforce	Global	Real-world implementation
[37]	IoT-BIM integration in prefabrication	System development and case study	IoT-BIM improves coordination and efficiency in on-site assembly	Technical complexity and data management	China	Scalable real-world validation
[81]	IoT in workflow automation	System architecture and case study	IoT enables real-time automation in repetitive construction tasks	Integration into existing workflows	USA	Broader application scenarios

Table 3. *Cont.*

Reference	Topic Focus	Research Method	Key Findings	Challenges/Limitations	Region	Research Gap
[92]	IoT-based safety verification system	System prototype and testing	Smart IoT can automate PPE tool matching to improve safety	Limited testing environments	China	Broader field deployment
[102]	3D printing with concrete extrusion	Literature-based roadmap	Identifies technical, material, and process priorities for 3DCP	Material consistency, process control	UK/Europe	Standardization and testing
[105]	3D printing in the construction industry	Critical literature review	Highlights benefits, barriers, and future potential of 3D printing	Material limitations, lack of standards	Global/China	Real-world implementation case

As shown in Table 3, most earlier studies tended to adopt a narrow scope, often concentrating on a single technology, for instance, BIM in cost estimation or IoT in safety monitoring. In contrast, our review takes a broader perspective by synthesizing insights across multiple technologies. This approach highlights synergies such as BIM–IoT integration and AI-driven digital twins, which remain relatively underexplored in the existing literature.

7.3. Limitations and Methodological Differences

Table 3 points to a clear imbalance: most studies focus on developed regions such as Europe, North America, and East Asia, while work on developing countries remains scarce, even though issues like cost, regulation, and workforce skills may shape adoption in very different ways. Methodologically, much of the existing research is built on conceptual models or small case studies, with few efforts using longitudinal or large-scale data. Our review highlights these gaps and underscores the need for more rigorous approaches to capture how technological adoption affects cost, productivity, and sustainability over time.

This review has some methodological limitations. It focused only on English-language publications from 2015 to 2025, which means that earlier or non-English studies may not have been captured. Although several major databases were searched (Scopus, Web of Science, ScienceDirect, and Google Scholar), it is still possible that some relevant studies were overlooked. In addition, no formal risk of bias tool was applied, since the review aimed at a thematic rather than a quantitative meta-analysis.

7.4. Contribution of This Review

This study builds on existing knowledge in several ways. It brings together evidence from 115 studies, offering a broader scope than most earlier reviews (Table 3). By quantifying technologies, benefits, and challenges (Table 1), it provides a clearer sense of research priorities, while visual summaries (e.g., Figure 2) make adoption patterns easier to grasp for both practitioners and policymakers. Importantly, rather than looking at technologies in isolation, this review highlights the value of integration, such as BIM, IoT, and AI ecosystems, which previous reviews have largely overlooked. We see this focus on integration as a key future direction and a distinctive contribution to our work.

Figure 3 shows how smart construction works as an ecosystem. Enabling technologies like AI, robotics, and blockchain support three main pillars: Industry 4.0, Digitalization/IoT, and 3D printing. Together, these pillars can improve efficiency, safety, and sustainability, though adoption is still limited by cost, skills, and regulatory barriers. The framework ties the review's themes into one model that can also be applied in other industries moving toward digital transformation.

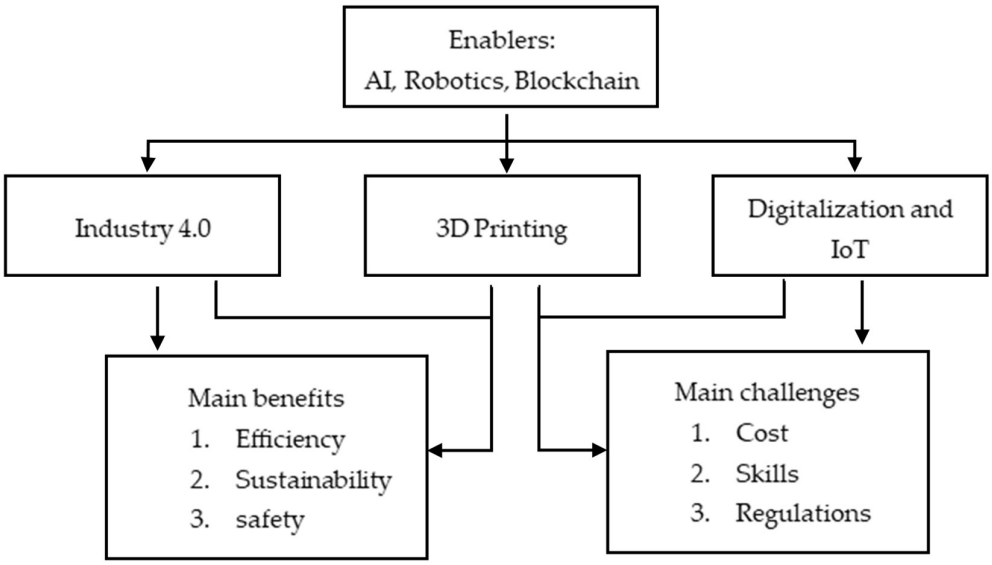


Figure 3. Conceptual framework of the smart construction ecosystem, integrating Industry 4.0, Digitalization/IoT, and Additive Technologies with cross-cutting enablers, benefits, and challenges.

7.5. Implications for Research and Practice

The findings suggest that the construction industry is shifting from small-scale experiments to wider use of Industry 4.0 tools. Still, Table 3 shows clear gaps; most research is concentrated in certain regions and often lacks long-term evaluation. For practitioners, BIM and IoT remain the most established, but fast-growing areas such as blockchain, robotics, and AI offer promising opportunities.

8. Recommendations and Future Directions

8.1. Recommendations for Practitioners

For construction companies looking to adopt Industry 4.0 technologies, the journey does not need to be overwhelming. A practical approach would be to start small and scale gradually. Technologies like BIM and IoT, which have already shown strong results in real-world projects like the Huzhou Qilitang smart site, as mentioned by [28,38], can be great starting points. These tools offer quick wins, such as better coordination, real-time data sharing, and improved safety on-site.

Another important step is to invest in people. Several studies, such as [67,68], have shown that one of the biggest barriers to digital adoption in construction is a lack of digital skills. Training programs tailored to all levels, from site laborers to project managers, can help build confidence in using smart tools and encourage buy-in across the company. These programs may take the form of modular online courses, on-site digital workshops, or blended training that combines practical hands-on sessions with e-learning modules. For companies concerned about high upfront costs, especially small and medium-sized firms, a phased strategy makes the most sense. This could involve adopting basic digital tools first, like cloud-based site monitoring or IoT safety wearables, before moving on to more complex systems like robotics or 3D printing [62,63]. Also, focusing on modular and flexible technologies, in line with the core principles of Industry 4.0, allows companies to upgrade without overhauling their entire system [47,51].

At a broader level, there is a need for clear guidelines and support from regulators and industry associations. Many companies are hesitant to fully adopt technologies like blockchain or 3D printing because of unclear standards or legal frameworks [41,114]. Government and professional bodies can play a big role by offering templates, certification programs, and standardized protocols that make adoption smoother and more reliable.

8.2. Recommendations for Researchers

While the benefits of Industry 4.0 in construction are widely discussed, there is still a gap when it comes to real-world evidence. The literature needs more case studies and data on how these technologies actually affect project outcomes like costs, schedules, environmental impact, and team collaboration [57,59,108]. Understanding these long-term effects will help both researchers and industry leaders make more informed decisions. Another important area that deserves attention is privacy and ethics, especially when it comes to IoT. With wearable sensors tracking everything from worker location to heart rate, it is essential to explore how to protect this data while still receiving value from it. Research should focus on solutions that are both practical and privacy-conscious. There is also a need to develop region-specific strategies. What works in a digitally mature market may not be suitable for places like India, Malaysia, or Vietnam, where there are different economic, cultural, and infrastructure realities. Researchers can help by tailoring frameworks that reflect these local conditions and constraints.

8.3. Future Research Directions

Looking ahead, future studies could explore how to better integrate multiple technologies, like combining IoT with BIM, blockchain, and 3D printing into a single smart construction ecosystem. Another exciting area is the use of AI and machine learning. These tools could help predict equipment failures, optimize schedules, or automatically adjust project plans based on real-time data. Lastly, policy and regulation will be key. Several technologies are advancing faster than the legal frameworks that govern them, particularly in emerging economies. Future research should focus on how to create flexible, supportive policies that can keep up with innovation without holding back progress.

9. Conclusions

This paper sets out to understand how Industry 4.0 technologies like IoT, 3D printing, and digital platforms are changing the way construction projects are planned, managed, and delivered. What's clear from the review is that these innovations are not just buzzwords; they are genuinely helping to solve long-standing issues in industry. Whether it is improving project timelines, reducing material waste, or making sites safer for workers, technologies such as Industry 4.0, IoT, smart sensors, and additive manufacturing are proving their value in real-world settings like the Huzhou Qilitang project and Dubai's Office of the Future. At the same time, it is also clear that the road to full adoption is not smooth. Many construction companies still face big challenges like high upfront costs, a lack of digital skills, unclear regulations, and, in some cases, resistance to change. These barriers are especially tough for small and medium-sized firms or those working in developing regions. The research shows that there is still a gap between literature and real life. Therefore, the potential here is enormous. If construction companies can take small, smart steps, starting with accessible tools like cloud-based monitoring or safety-focused IoT wearables, they will be moving in the right direction. And for researchers, there is plenty of room to keep the momentum going by focusing on the real-world impact of these technologies, especially in regions where the industry is still catching up. Overall, the shift to smart construction is not just an upgrade, it is a chance to reimagine how the entire industry operates.

For SMEs, a roadmap can be used to make the adoption of these technologies easier. Firms can start by assessing their current digital situation and identifying the areas that need to be developed. Later, firms can start practicing these technologies in a small project to test how reliable and measure returns. Firms also need to make sure to provide tailored

training for their workforce and have a partnership with technology providers. Finally, firms need to align their strategy with the current regulations policy to ensure sustainability.

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