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Systematic Review

Integration of Blockchain and Digital Twins in the Smart Built Environment Adopting Disruptive Technologies—A Systematic Review

Habib Sadri [1,*], Ibrahim Yitmen [1], Lavinia Chiara Tagliabue [2], Florian Westphal [3], Algan Tezel [4], Afshin Taheri [5] and Goran Sibenik [6]

1 Department of Construction Engineering and Lighting Science, School of Engineering, Jönköping University, Gjuterigatan 5, 551 11 Jönköping, Sweden
2 Department of Computer Science, University of Turin, Corso Svizzera 185, 10149 Turin, Italy
3 Department of Computer Science, School of Engineering, Jönköping University, Gjuterigatan 5, 551 11 Jönköping, Sweden
4 School of Engineering and Applied Science, Aston University, Birmingham B4 7ET, UK
5 Pythagoras AB, Söder Mälarstrand 27B, 118 25 Stockholm, Sweden
6 Institute of Building and Industrial Construction, Integrated Planning and Industrial Construction, Vienna University of Technology, 1040 Vienna, Austria
* Correspondence: habib.sadri@ju.se

Abstract: The integration of blockchain and digital twins (DT) for better building-lifecycle data management has recently received much attention from researchers in the field. In this respect, the adoption of enabling technologies such as artificial intelligence (AI) and machine learning (ML), the Internet of Things (IoT), cloud and edge computing, Big Data analytics, etc., has also been investigated in an abundance of studies. The present review inspects the recent studies to shed light on the foremost among those enabling technologies and their scope, challenges, and integration potential. To this end, 86 scientific papers, recognized and retrieved from the Scopus and Web of Science databases, were reviewed and a thorough bibliometric analysis was performed on them. The obtained results demonstrate the nascency of the research in this field and the necessity of further implementation of practical methods to discover and prove the real potential of these technologies and their fusion. It was also found that the integration of these technologies can be beneficial for addressing the implementation challenges they face individually. In the end, an abstract descriptive model is presented to provide a better understanding of how the technologies can become integrated into a unified system for smartening the built environment.

Keywords: blockchain; digital twin; Internet of Things; artificial intelligence; technology fusion; building industry

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1. Introduction

Despite its crucial role as one of the most momentous drivers of economic growth, the building industry has long been dealing with issues such as low productivity, delayed payments, poor regulatory compliance and communication, lack of trust among stakeholders, and fragmentation of the information value chain [1–3]. At the same time, the implementation of smart devices and sensors to collect data and meticulously monitor the built environment has led to the accumulation of an enormous amount of raw data (i.e., Big Data) that are almost impossible to be aligned, annotated, and processed manually and through the traditional methods [4]. Blockchain, Digital twin (DT), Internet of Things (IoT), and artificial intelligence (AI) are among the disruptive technologies, the integration of which is deemed highly promising for addressing the identified challenges [5,6].

The contemporary built environment is seeing a significant increase in the adoption of DTs, as they provide the capability of enhancing collaboration and information communication across the asset lifecycle by providing a digital representation of the physical world [7]. They also make it possible to monitor the real-time behavior of actual assets by employing virtual models to keep the stakeholders updated with the performance of the asset in its current situation [4], as well as recommending analytics-based decision-making for smart asset management [8].

As information technology (IT) evolves, DTs have experienced essential alterations and become the backbone of smart built environments, hosting other listed technologies for implementation and integration. Nevertheless, this technology is still in its infancy mainly implemented for prototyping, modeling, and confirmation of physical artifacts through simulated replicas [9]. Moreover, in practice, DTs are chiefly employed in a fragmented manner, particularly over the building operation and maintenance phase [7].

In order to pave the way for the use of digital approaches to design, build, operate and maintain, and integrate the built environment in a more efficient way, the Centre for Digital Built Britain (CDBB) has introduced a group of values, called the Gemini Principles [10,11], emphasizing information value management in such a way that data volume decreases while data value is increased. Among the key pillars in the Gemini Principles are data trustworthiness, security, quality, and openness, which are at the same time reminiscent of the main characteristics of blockchain, as a popular type of distributed ledger technology (DLT). This concurrency makes blockchain an appropriate technology to fulfill the Gemini Principles' demands [3]. Moreover, decentralized applications, relying on decentralized databases and distributed ledgers, will avoid single sources of trust and provide a secure model for lifecycle information exchange in a complex ecosystem where the stakeholders interact with DTs. This approach, while ensuring the required integrity, confidentiality, and availability, can propitiously address the data exchange challenges [12]. Having blockchain employed, the legitimacy of transactions would be ensured, and high-value transactions can be facilitated using cryptography and consensus mechanisms for verification and traceability. Therefore, the implementation of blockchain in the building industry and its integration with DTs and building information modeling (BIM) for lifecycle information management provides great potential to deal with issues regarding trust, transparency, and communication [5].

Benefiting from IoT-enabled sensors, as mentioned, DTs can offer a living instrument for a kind of "up-to-current" modeling [6]. Beyond that, empowered DT with AI will be able to simulate different "what-if" scenarios for predictive and preventive maintenance [13] and put forward effective solutions to potential issues before they arise [6,14]. The cognitive capabilities of DTs, which have stemmed from the adaptation of AI, also result in persistent calibration, integration, and info-symbiotic connectivity between the physical asset and the virtual replica [9,15–17].

This study, through scrutinizing the recent research carried out in the field, attempts to depict an overview of the research trends, and reveal the potential of the introduced technologies in the building industry. It is also intended to shed light on the publication patterns and detect the state of the art by performing in-depth bibliometric analyses. Therefore, the objectives of the research can be articulated as follows:

- Elucidate the status quo and research trends on the foremost among the enabling technologies in the integration of blockchain and DTs in the building industry.
- Assess the scope of applicability and fusion capabilities of these technologies.
- Disclose the research gaps and further development opportunities.

In this way, Section 2 articulates the research method and data collection course of action. Section 3 presents bibliometric analyses of the recent literature to statistically illuminate the research trend. Section 4 provides a brief overview of the targeted technologies and their characteristics, followed by an exploration of their fusion from the perspective of the previously conducted research presented in Section 5. Considering the insights obtained from the investigation of the literature, Section 6 offers an abstract model illuminating the configurative and synergistic form of such a technology fusion, as well as highlighting the identified gaps in the literature and the prospective directions for future works. Finally, Section 7 delivers a brief conclusion of the study. Figure 1 briefly outlines the steps followed in this paper.

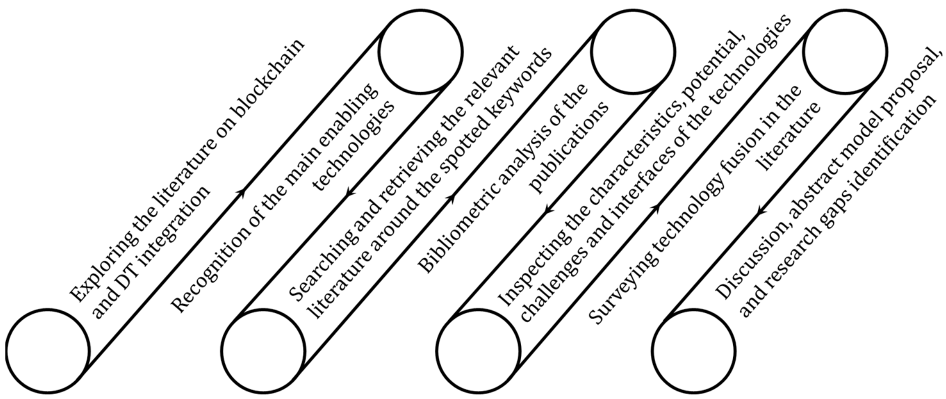

Figure 1. The study path and steps.

2. Research Method and Data

Conducting a thorough literature review is necessary to provide and consolidate the foundation of knowledge on a topic, identify potential research gaps and challenges, and probe into the prior scientific efforts to extract bright ideas and avoid repetitive research [18]. In this regard, contrary to traditional narrative reviews, where the studies are substantially orientated by the researchers' recognition and most probably suffer from a lack of thoroughness [19], a systematic literature review is an approach in which the system neutrally identifies the target literature and leads the researcher to the conclusion ensuring the transparency of the process and robustness of the results.

Therefore, in this study, the eight-step guide to planning, selection, data extraction, and execution of a systematic literature review, recommended by Okoli and Schabram [20] is followed. At the planning stage, the purpose of the literature review is clearly identified, and all the reviewers agree upon a thorough research protocol and are trained accordingly. Then, the selection of the literature includes the next two steps, viz., searching for the literature, screening for inclusion. Subsequently, at the extraction phase, the quality appraisal takes place, which is, in other words, the screening for exclusion, followed by data extraction when the reviewers draw and collect the relevant information from the included studies. Eventually, the execution phase consists of the two last steps, namely, analysis of findings, also known as the synthesis of studies, which is combining the extracted facts through qualitative and/or quantitative techniques, and writing the review, where the study results along with the review process are described in sufficient detail so that the findings can be reproduced independently. A comparable approach is also recommended by Xiao and Watson [21], which outlines the main steps of a successful review in a similar way.

This study has also applied Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), as a set of guidelines for reporting systematic reviews and meta-analyses to combine the results of multiple studies to provide a more precise estimate of the overall effect of the investigated technologies [22]. Table S1 in Supplementary Materials provides the related checklist.

2.1. Indexing the Query Terms

As an initial step to define the research boundaries, a preliminary search was performed through the Scopus and Web of Science search repositories with two main keywords, namely, "digital twin" and "blockchain". The 161 detected documents were inspected in VOSviewer [23] to discover the most common associated keywords through their density in the co-occurrence network, as visualized in Figure 2. As a result, "Internet of Things (IoT)" and "Artificial Intelligence (AI)" were identified as the two major concomitant technologies in the body of the latest research. Therefore, five keywords were considered for the literature search, which are elaborated in Table 1, along with their synonyms to formulate the eventual search strings.

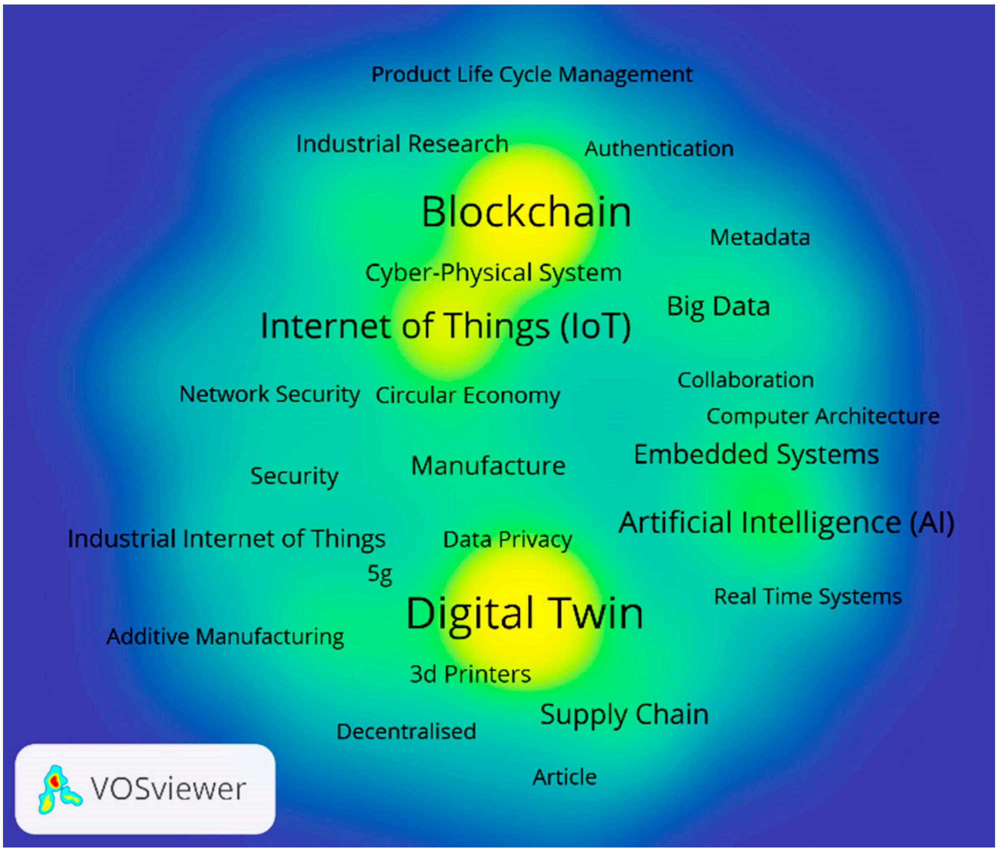

Figure 2. The density of keywords around "Blockchain" and "Digital Twins" in the literature.

Table 1. The implemented search strings based on the study keywords.

1	(blockchain OR block-chain OR "block chain" OR "smart contract*" OR "distributed ledger technolog*")
2	"digital twin*"
3	("internet of things" OR iot OR iiot)
4	("artificial intelligence" OR "machine learning" OR "deep learning")
5	("AEC* industry" OR "construction industry" OR "building industry" OR "built environment")

2.2. Study Retrieval and Selection

In this phase, having identified the query terms, the search was once again carried out in the Scopus and Web of Science databases, limited to the papers' title, abstract, and keywords. Furthermore, only peer-reviewed articles, conference papers, book chapters, and reviews in English and within a period of five years (2017–2022) were included. The composed search strings and their combinations are formulated as presented in Table 2.

Table 2. The selected databases and formulated search strings.

Database	Search String
Scopus	TITLE-ABS-KEY (((“AEC* industry” OR “construction industry” OR “building industry” OR “built environment”) AND (blockchain OR block-chain OR “block chain” OR “smart contract*” OR “distributed ledger technolog*” OR “digital twin”) AND ((“artificial intelligence” OR “machine learning” OR “deep learning”) OR (“internet of things” OR iot OR iiot)))) AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”) OR LIMIT-TO (DOCTYPE, “re”) OR LIMIT-TO (DOCTYPE, “cr”) OR LIMIT-TO (DOCTYPE, “ch”)) AND (LIMIT-TO (LANGUAGE, “English”))
Web of Science	((TS = ((“AEC* industry” OR “construction industry” OR “building industry” OR “built environment”))) AND TS = ((blockchain OR block-chain OR “block chain” OR “smart contract*” OR “distributed ledger technolog*” OR “digital twin”))) AND TS = ((“artificial intelligence” OR “machine learning” OR “deep learning”) OR (“internet of things” OR iot OR iiot))

As a result of the inquiries and after assessing the emerged documents in terms of their content and availability as well as including other literature through snowballing, 86 papers were retrieved as the review sources. Figure 3 represents the steps in paper identification and selection in the form of a PRISMA flow diagram.

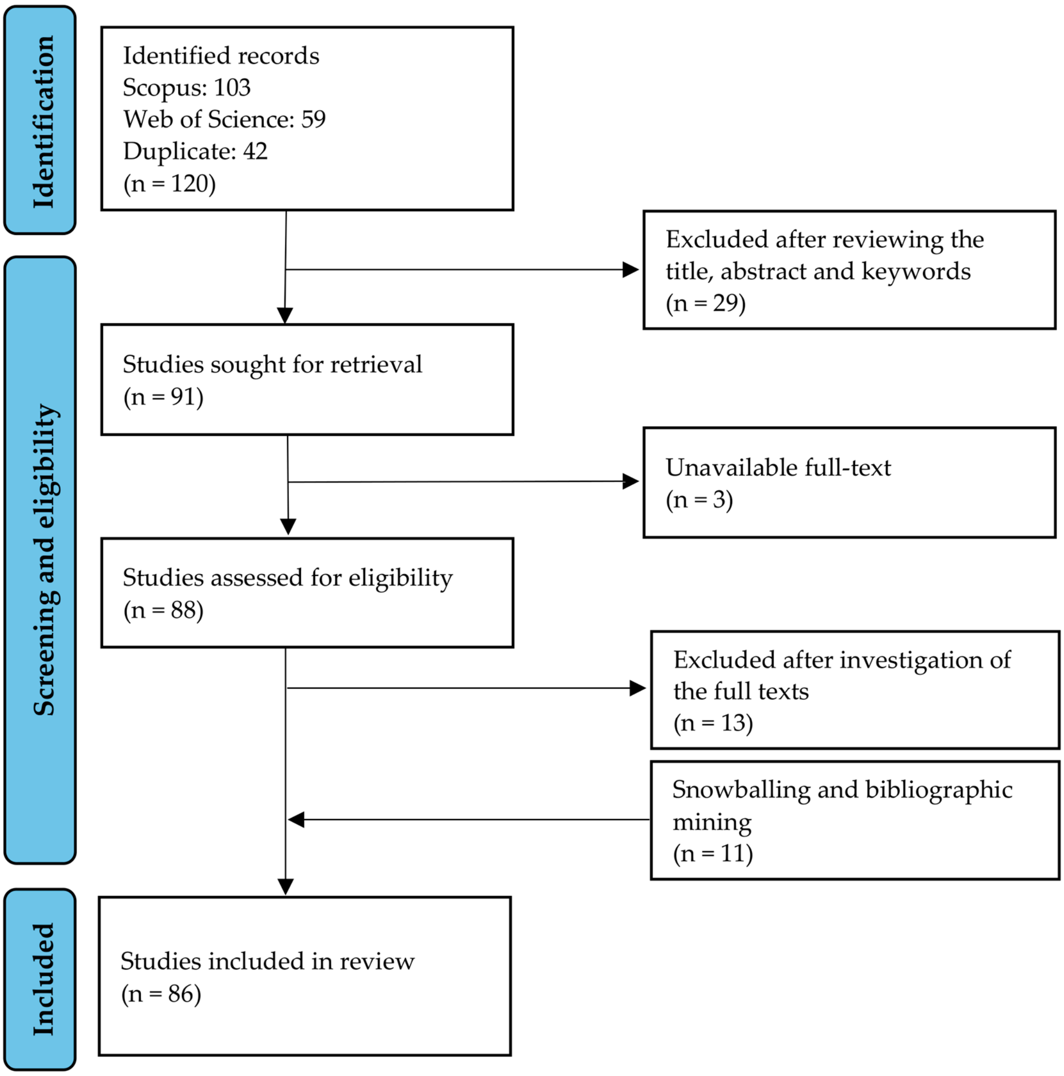

Figure 3. PRISMA flow diagram presenting the retrieval and screening process of the literature.

2.3. In-Depth Analysis and Review

After retrieving the identified articles, a series of bibliometric analyses were carried out using VOSviewer, the results of which are elaborated in detail in the following section. Bibliometric analysis, as a rigorous method for dissecting large scientific data sets, makes it possible to detect the subtle evolutionary nuances in a particular field of research, while elucidating the emerging areas in that field [24]. Subsequently, the discussed disruptive technologies, their predominant features and characteristics, and their potential for integration with each other in the building industry are explored by inspecting the body of the recent research.

3. Descriptive Bibliometrics

This section will statistically explore the selected literature and the trend of research on the highlighted disruptive technologies in the building industry through a thorough bibliometric analysis. Research on the integration of technologies in the retrieved literature started in 2017 by working towards functional DTs in combination with IoT, offering cost-effective and scalable solutions for the underground built environment [25], followed by the integration of blockchain and AI in 2018, focusing on trust issues in the real-estate economy [26]. Figure 4 shows the number of annual publications integrating these technologies into the building industry. As can also be seen in this figure, the vast majority of the studies have been conducted from 2020 onwards.

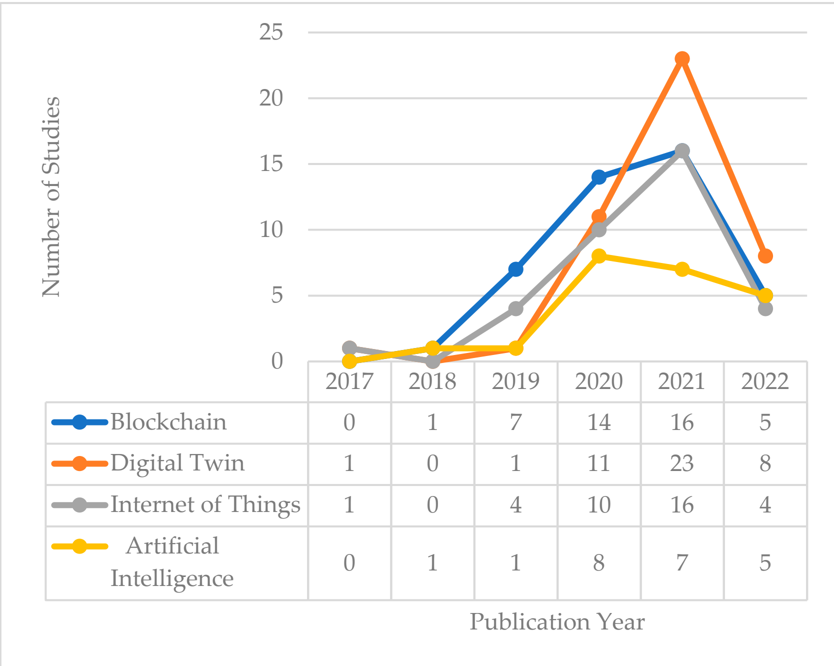

Figure 4. Number of research published annually focusing on integration of different technologies within the building industry.

As a network visualization tool for generating maps based on network data as well as exploring and visualizing them [27], VOSviewer is utilized for the bibliometric analyses in this study. Prior to conducting these analyses, thesauruses were created to merge the duplicate items and normalize the terms, as a single concept may have been referred to in multiple forms (e.g., digital twin and digital twins). After inserting the retrieved records and generated thesauruses into the software application, the intended analyses were carried out, the results of which are presented in the following sub-sections.

3.1. Co-Authorship and Authors

As illustrated in Figure 5, a "co-authorship" analysis of the selected literature was performed, considering "authors" as the unit of analysis. In this analysis, the minimum number of documents for each author is 2, and the number of selected authors is 30, accordingly. The size of the nodes in this figure depends on the number of the authors' literature while the connecting lines between them indicate the collaboration between different authors. The color spectrum in the left graph represents the average publication years of the articles published by each author, and in the right one indicates the average number of citations they have received. Samudaya Nanayakkara and Sepani Senaratne, with 2 papers and an average of 66.5 citations, are the most cited authors, while Yacine Rezgui with an average of 56.7 citations in 3 papers, and Jennifer Li and Mohamad Kassem with an average of 56 citations in 3 documents are the next most cited authors.

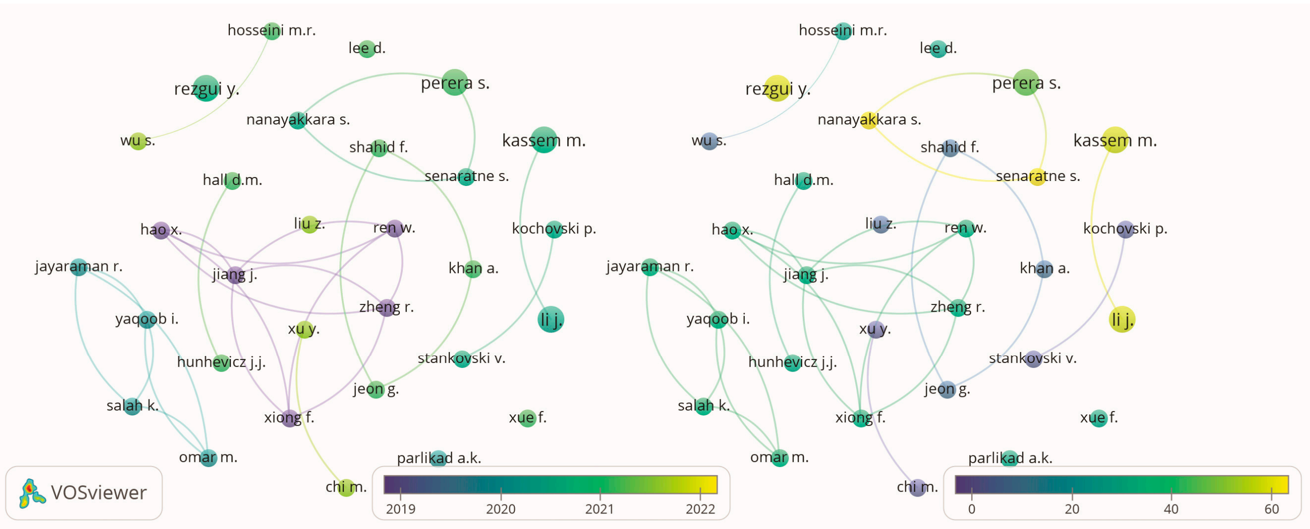

Figure 5. Co-authorship analysis with "authors" as the unit of analysis.

3.2. Co-Authorship and Countries

The result of the country-based co-authorship analysis of the investigated documents is shown in Figure 6, where the size of the nodes implies the number of published papers and the linking lines between them show the international collaboration in research. The colors in the left graph represent the average publication years, while the colors in the right one indicate the average number of citations. In this analysis, the minimum number of documents for each country is considered to be 2, and the number of considered countries is 18 accordingly. As clearly appears from the graphs, the United Kingdom is the country with the highest number of publications with 22 published articles and an average of 28.5 citations. Then, the United States, Australia, and China have the largest number of publications with 15, 14, and 11 published papers and 13.3, 20.9, and 15.2 citations on average, respectively. A quick look at the average publication years of the literature reveals that most of the research in the field is carried out in the last year, while the time span for the literature search was from 2017 to (mid-)2022. This implies that the integration of the intended technologies into the building industry is quite pristine and the quantity of research on it is increasing exponentially.

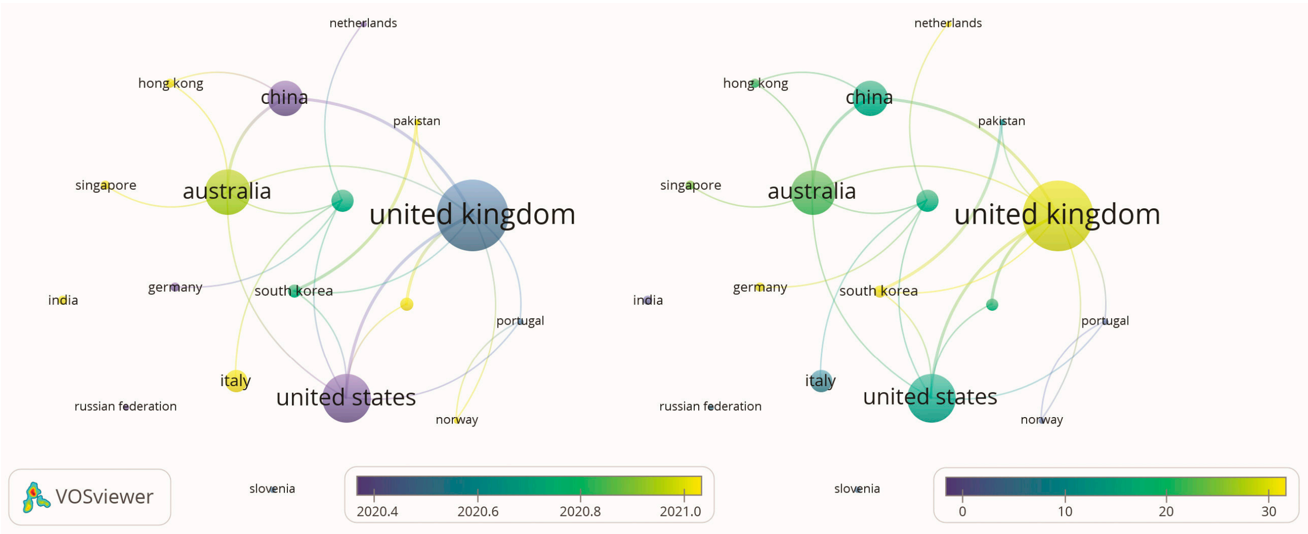

Figure 6. Co-authorship analysis with "countries" as the unit of analysis.

3.3. Co-Occurrence of Keywords

The co-occurrence of keywords in the selected documents is another form of bibliometric analysis conducted in this section that sheds light on the frequency of occurrence of keywords as well as their distribution over time and their interconnection together, the results of which are shown in Figure 7. The minimum number of occurrences of a keyword in this analysis is set to 5, which leads to the display of 29 keywords. The size of the nodes in this figure indicates the number of occurrences of each keyword, while the connecting lines between them imply the co-occurrence between them in the literature. The thicker the linking lines between the nodes, the stronger their connections and the more frequent their co-occurrence. The minimum link strength in this graph is set to five, which means the keywords connected in this graph have co-occurred at least five times. The color spectrum in this graph represents the average publication years of the literature containing the keyword. "Building industry", "digital twin", "blockchain", and "internet of things" are the most frequently co-occurring keywords in the 86 selected documents with 41, 40, 37, and 34 occurrences, respectively. A glance at the color of the nodes reveals the fact that "decision making", "supply chain", and "facility management" are among the most recent research trends.

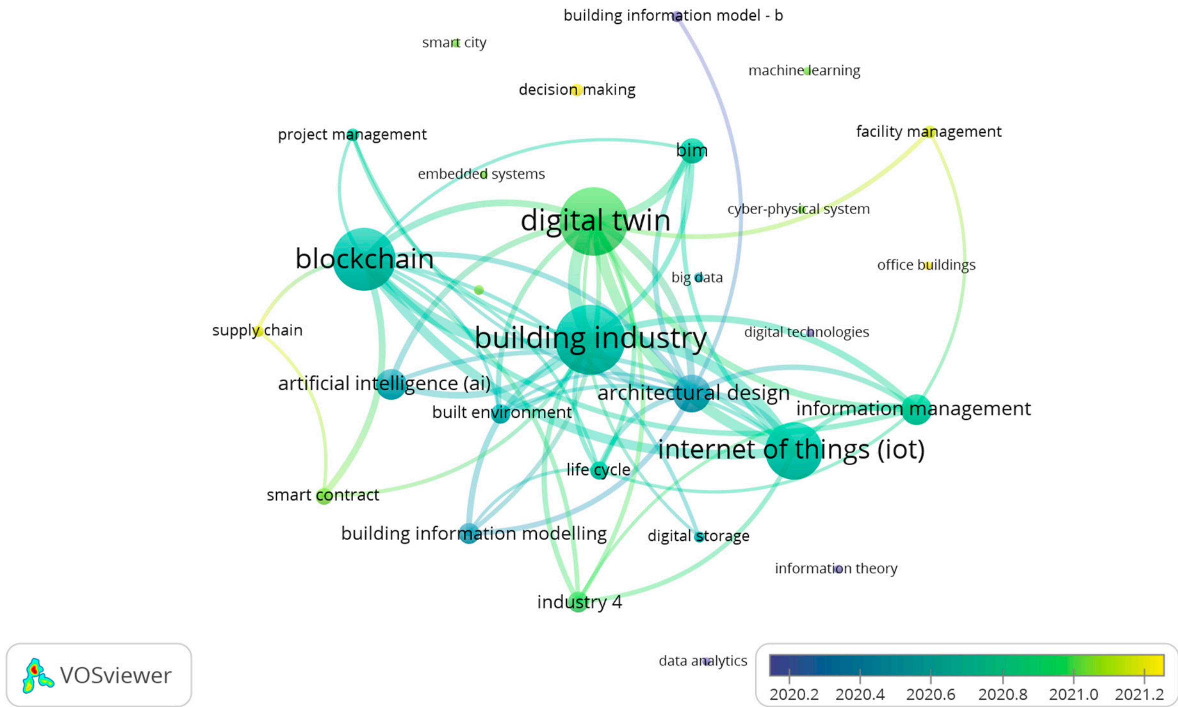

Figure 7. Co-occurrence of keywords.

3.4. Citation of Documents

Figure 8 is generated based on an analysis of the literature citations. In this analysis, the minimum number of citations of a document to be displayed is 10, which includes 40 documents in the graph. The weight of each node is affected by the number of received citations, and the lines connect the literature that has cited each other, while the colors in this graph change based on the literature publication year. Boje et al., (2020) [28], Li et al., (2019) [29], Singh et al., (2020) [30], and Perera et al., (2020) [31] are the most cited literature with citation indices of 167, 155, 146, and 124, respectively.

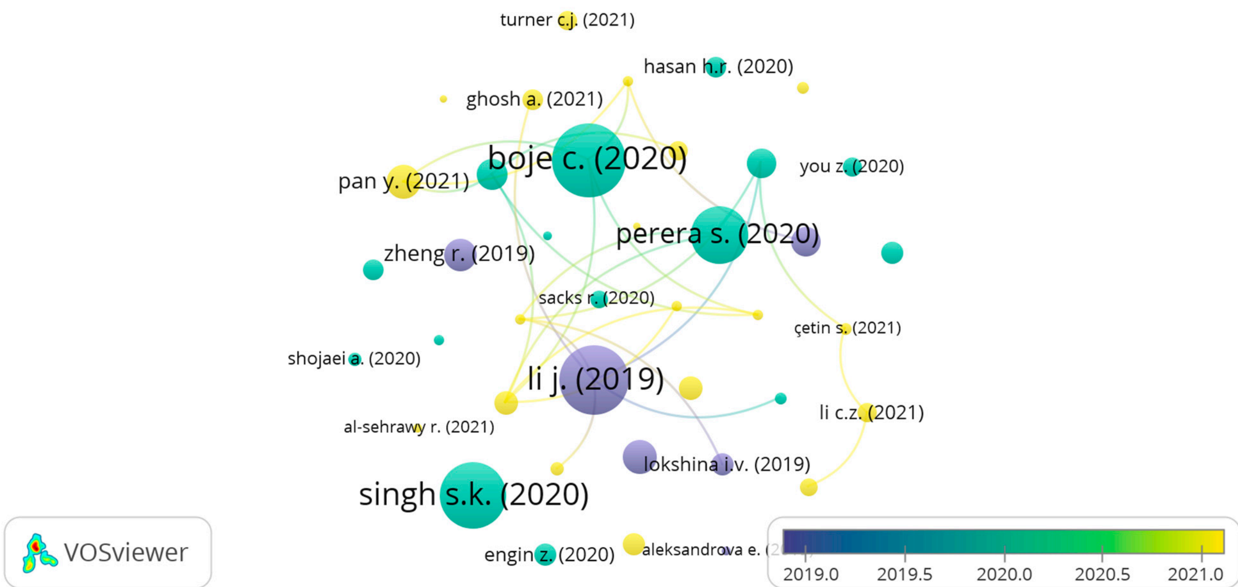

Figure 8. Citations of the literature indicating the most cited literature [28–31].

3.5. Bibliometric Coupling of Sources

The last performed analysis using VOSviewer is the bibliometric coupling of sources that elucidates the trend of publications and citations among various sources (e.g., journals and conferences) resulting in Figure 9. Here, 56 sources were recognized, publishing the selected literature, represented by the nodes in the graph. The diameter of the nodes corresponds to the number of published documents, reviewed in this study and the linking lines show the number of cited references between the sources, while the thicker lines mean more mutual citations. In this graph, the minimum line strength is set to 10, which means only connections between sources that have cited each other at least 10 times are displayed. The colors in the left graph represent the average publication years of literature published in each source, and in the right one indicate the average number of citations they have received. As can be seen in the graph, the *Journal of Automation in Construction*, with 14 papers and far beyond the other sources, has the largest number of publications, followed by the MDPI journals of *Buildings*, *Sustainability*, and *Applied Sciences*, with 5, 4, and 4 articles, respectively. On the other hand, the journals of *Future Generation Computer Systems* and *Industrial Information Integration* are the most cited sources, receiving an average of 146 and 120 citations, respectively. Each of these two journals has only one article in the list of the considered literature.

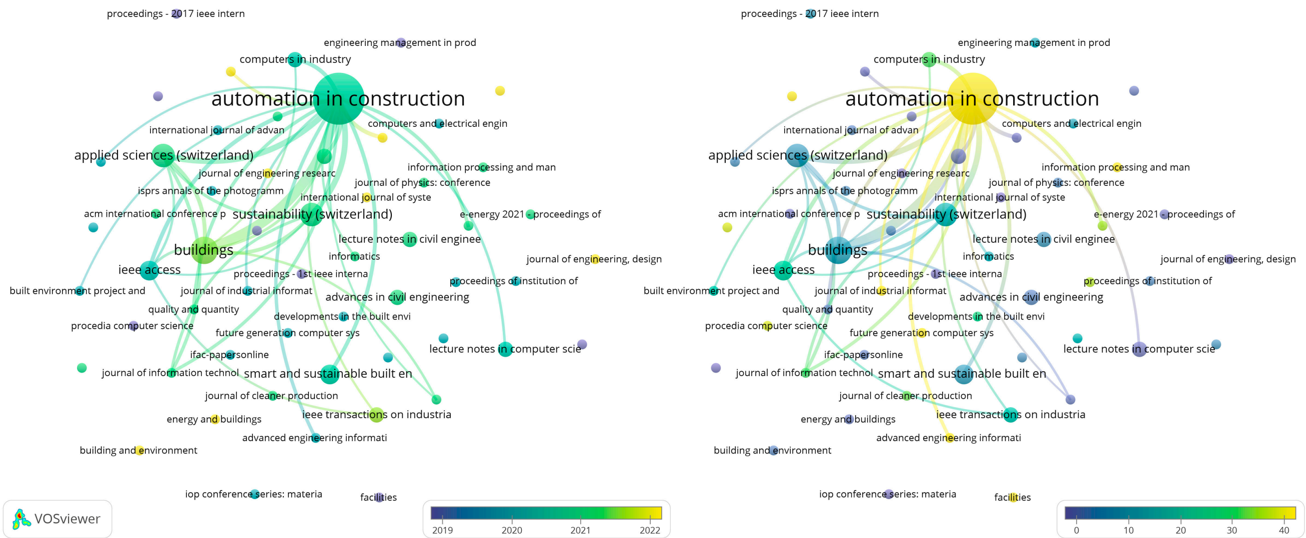

Figure 9. Bibliometric coupling of sources.

4. A Panorama of Disruptive Technologies

This section provides an overview of the highlighted technologies to provide a better insight into their concepts, the possibilities they offer for integration with each other, and the opportunities they afford to improve smarter build environments, as well as identifying their implementation challenges and potential remedies.

4.1. Blockchain—The Game-Changing Paradigm

Blockchain, constituted based on Distributed Ledger Technology (DLT), is a technology developed for recording transaction data on successive blocks, chained together through cryptography and hashing techniques [32]. Here, integrity is enforced and verified through a distributed process and decentralized consensus procedure. Blockchain can also be the placeholder for the crucial data and the transactions by built environment agents as well as being implemented as an enforcement mechanism for procedures and policies [33]. Among the other prominent technical features of blockchain for information exchange are trust, traceability, transparency, anonymity, security, connectivity, and automation [34,35]. Contract management, information management, supply chain management, and stakeholder management are among the applications of blockchain in the building industry that have recently received the most attention from researchers in this field [36].

There are three types of blockchain infrastructure, namely public, private, and consortium blockchain. Public blockchain, also called permissionless, is an open network for any participant to join freely, see the shared ledger, and contribute to the consensus process and validating transactions. Herein, the consensus mechanism is proof-of-work or proof-of-stake. It offers the highest level of decentralization, but the lowest transaction speed [37–39]. On the other hand, private blockchain is a network, where a central authority determines the participants, their roles, and the transaction permission [39,40]. Private blockchain is the fastest in terms of transaction speed, while it is less decentralized [41]. Consortium blockchain, also known as federated or permissioned blockchain, is a semi-private and multi-organizational solution for allied businesses, emerging as a middle ground between private and public blockchain. A consortium blockchain has privileged permissioned nodes over the network, however, there is no single owner organization. In terms of privacy and performance, it benefits from the same advantages as private blockchain, while it is governed by a group [31,38,39,41]. Concerning decentralization and transaction speed, consortium blockchain is at a medium level compared to public and private blockchain. The consensus mechanism for both private and consortium blockchain is a voting or multi-party consensus algorithm [41].

None of the three types of blockchain infrastructures is generally superior to the others, but each type is developed to serve different purposes. For instance, private blockchain can provide solutions at the enterprise level. Supply-chain management and keeping the transaction records for corporations with limited transaction requirements are some potential applications. Public blockchain can be implemented for handling the data, where the data need to be openly exposed to public auditability. Hence, it is a popular infrastructure for peer-to-peer transactions and cryptocurrencies. Due to its customizability, consortium blockchain would be suitable for an overall project ecosystem, where for instance, banks or other organizations want to control the participation and access levels in the network [3,39].

Tokenization, in the blockchain context, refers to the process of converting assets of any kind, either tangible or intangible, into digital tokens. This concept has recently gained plenty of traction within the industry and is gradually becoming adapted to conventional industries such as real estate, artwork, and equities [42]. Tokenization can, for instance, provide a bedrock for monetizing the capacity of idle items on peer-to-peer networks to make the most of assets through blockchain-based crowdsourcing, which has been discussed as a promising approach to overcoming the deficiencies of traditional centralized crowdsourcing systems, such as Sybil attacks and single point of failure [43,44]. As a decentralized alternative to obtaining project funding, blockchain-based crowdsourcing offers advantages such as opening doors for talented individuals in economically underdeveloped countries, obviating the need for intermediaries, and codifying agreements with auditable terms to support fair contract executions [45,46].

4.1.1. Smart Contracts

The term smart contract was first coined by a cryptographer, Nick Szabo, in 1994, as a computerized transaction system to perform the contract provisions [40], fully executable, independent of human interference [47]. After the advent of blockchain technology and due to its enabling infrastructure, the smart contract concept was brought into the spotlight for automating legal contracts [48] and removing the third parties in transactions [49]. Smart contracts are pieces of computer codes with some conditional statements in the form of ''if/then'' [50], general features of which can be characterized as (1) self-executing, so that they are triggered by transactions and take place without the necessity of manual interaction; (2) self-enforcing, as once smart contracts are initiated, they cannot be prevented from execution; (3) transparent, when smart contracts are acknowledged by each node in the blockchain network, because their correctness needs to be verified by most of the nodes; and (4) flexible, as smart contracts can adapt to different scenario requirements [51,52].

Organizing the project's payments regarding construction, operation, and maintenance activities is one of the most noted use cases of smart contracts by researchers, as, upon completion of each task by contractors, the corresponding payment can be triggered through performance-based smart contracts in a safe and autonomous manner with a higher execution speed [8,31,49,53]. As an instance, Ahmadisheykhsarmast and Sonmez [54] have presented a smart contract approach for the security of payments in construction contracts through an automated decentralized protocol, while addressing the issues of trusted intermediaries and eliminating the administrative costs. Moreover, Nanayakkara et al. [38] conclude from their research that smart contracts and blockchain-based solutions can significantly improve payment procedures, particularly in terms of partial payments, long payment cycle, non-payments, cost of finance, retention, and security of payments. Likewise, Chong and Diamantopoulos [55], as well as Liu et al. [56], discuss how the integration of blockchain-based smart contracts and BIM models can in different contexts address issues regarding the security of payments within the building industry. Moreover, in order to ensure accuracy, timeliness, and efficiency of payment administration, Hamledari and Fischer [57] proposed a framework for construction payment automation based on smart contracts, while robotic reality capture-technologies were utilized to document the progress at the construction site. The automated project bank account is also a functional use case of smart contracts, studied by Li et al. [29], asserting the potential of smart contracts to embed the project's funds and protect all the contractors and supply chain stakeholders against insolvency as well as automating the payment principles. This approach will at the same time increase transaction efficiency, decrease payout time, and minimize operational risks, back-office costs, and the risk of fraud. However, such applications of smart contracts are also not challenge-free, as they are prone to various security issues such as programming vulnerabilities, different types of attacks, and other inherent susceptibilities stemming from their technical structure [58].

4.1.2. Decentralized Applications and Organization

Decentralized Applications (DApps) are open-source blockchain-powered applications that enable user interaction with smart contracts through web-based user-friendly interfaces [12]. The application logic in DApps is entirely decentralized, as the user's browser executes the front-end code and the smart contracts run the back-end code on the blockchain nodes. This decentralization in the application yields full transparency of the codes as well as the auditability of modifications in the state of the smart contract [12]. Decentralized autonomous organization (DAO), as a quite similar concept, refers to entirely autonomous smart contract-based organizations that operate on peer-to-peer networks with no need for human involvement [2,59]. This independence from human interaction is the main distinction between DApps and DOAs. In other words, each DAO is a DApp, while each DApp is not necessarily a DAO [49].

Capitalizing on DAOs for the integration of BIM, IoT, and blockchain, Ye et al. [60] have tried to propose an efficient solution for building operation and maintenance to mitigate labor and administration costs as well as addressing health and safety issues. Cho et al. [61] also take advantage of DApps in their proposed framework to organize the interaction between actors in different roles for fine dust management at the construction site. Nevertheless, industrial implementation of DAOs also faces some challenges such as an unclear legal status, security issues, and technical limitations [62].

4.1.3. Implementation Challenges

Blockchain, as an emerging paradigm for data exchange in the industry, struggles with challenges of two major types. First, those stemming from blockchain nascency, which, in general, only require the passage of time until this technology is gradually adapted to the industry. Lack of adequate skilled developers and operators [63,64], public awareness and acknowledgment [63,65], and integration with legacy systems [66,67] are among the challenges of this type. The other category comprises the challenges originating from the inherent technical features of this technology, including data privacy issues [67,68], scalability issues [30,69–71], energy consumption [30,67], and vulnerability to quantum attacks [69,72]. However, potential approaches to address challenges of the second type are discussed in the literature, some of which will be mentioned in the following section.

4.1.4. Data Handling Approaches and Opportunities

Data handling and storage is one of the most controversial issues in blockchain implementation and the main basis of the aforementioned technical challenges. Blockchain is not well suited for storing Big Data due to the high velocity and huge volume of data [73]. Therefore, a practicable solution is to split the data into two categories, namely on-chain and off-chain. On-chain data include the crucial data that must be on the blockchain, while other voluminous data sets remain off-chain [31]. For instance, Lee et al. [6] in their case scenario keep only a 0.5-kilobyte document on-chain, while the 876-megabyte BIM model, used for feeding the digital twin, stays off-chain. Thus, off-chain storage is deemed to be a promising solution to the scalability issues, while mitigating on-chain storage costs [67]. By restricting access to data to authorized users, data privacy is well considered in private blockchains, while this is a drawback to public blockchains [37]. Off-chain storage is also discussed as a means to overcome privacy issues, as it can store confidential or sensitive information even in public blockchains [73]. By the same token, taking advantage of a private InterPlanetary File System (IPFS), as a distributed data sharing approach, can also offer benefits in terms of privacy and storage cost [74].

Nevertheless, it must be pointed out that parallel to data privacy enhancement and storage cost reduction, as significant advantages of off-chain data storage, security of data and validity of transactions, on the other hand, would be adversely affected. In other words, there is always a trade-off between more trustworthy but also more expensive on-chain data storage and more preserved privacy but less trustworthy off-chain data storage [8,57]. Furthermore, another noteworthy point in this regard is how to maintain real-time state consistency (and transaction conformation) between off-chain and on-chain data [75]. This is where the concept of oracles comes into play. As a third-party service, oracle is a mechanism that provides smart contracts with tamper-proof off-chain data, enables various parties and information sources to become involved in smart contract-based activities, and therefore, links the outside world to blockchain [47,76,77].

Sharding, a mechanism originally designed for the horizontal partitioning of databases, is also intended to overcome blockchain scalability barriers over the Ethereum network, without compromising the security of the network and its decentralization. Splitting the transaction load amongst smaller groups of nodes, known as "shards", and processing them in parallel, the sharding scheme enables the distribution of storage and computing workloads on the blockchain network and alleviates the load on nodes, as they do not all have to process the transaction load of the entire network. This parallel transaction technique is deemed to significantly enhance the blockchain network throughput [31,75].

Table 3 summarizes the research focus and outcomes of the retrieved studies pivoting around the implementation of blockchain in the building industry.

Table 3. Literature on blockchain implementation in the building industry.

Reference	Year	Research Focus Utilizing Blockchain	Outcome
Singh et al. [30]	2020	Big Data analysis, security and privacy, decentralized architecture, AI, IoT	A Blockchain-based IoT architecture for Big Data analysis
Putz et al. [12]	2021	Decentralized applications, DT information management, security and trust between different parties	An owner-centered decentralized data sharing model
Shojaei et al. [70]	2019	Built asset sustainability, decision support, supply chain information management	A blockchain-driven model supporting built asset sustainability
Lee et al. [6]	2021	Information sharing and accountability, enhancing DT communication, near real-time information update through IoT sensors	A framework for integration of DTs and blockchain supporting accountable information sharing
Hunhevicz et al. [8]	2022	Performance-based smart contracts, built environment as a service, performance evaluation and accountability	A full-stack blockchain-based DT architecture to support performance-based payments
Li et al. [78]	2021	Prefabricated housing construction sustainability, smart product-service systems, IoT	An intelligent blockchain-IoT platform to enhance smart construction processes
Rane and Narvel, [79]	2022	Project resource management, data-driven decision making, heavy construction assets maintenance	A blockchain-IoT architecture for project resource management processes capturing the real-time data from heavy equipment
Siountri et al. [80]	2020	BIM security issues, digital transformation in the building industry, IoT	Blockchain-driven system architecture to securely adopt IoT and BIM-based systems
Siountri et al. [81]	2019	Smart museum, security and privacy, information systems applications, IoT	A system architecture integrating BIM, IoT and blockchain to advance a smart museum building
Shahid et al. [82]	2020	Quantum cryptography, post-quantum digital signatures, ledger scalability, light-weight consensus	A quantum-secure distributed ledger for IoT systems
Khan et al. [83]	2020	Quantum resilient blockchain, immediate transaction confirmation, common DT conceptualization	A quantum-resilient blockchain model to efficiently manage DT data
Adel et al. [1]	2022	AI decision verification, confidential data sharing, and ownership traceability	A three-layer architecture for decentralized AI systems as an inference engine supported by a case study of construction cost estimating

4.2. Digital Twin—A Live Mirror of the Asset

Since its introduction in 2002, a variety of different definitions and conceptualizations for digital twin have been presented, the overlap between which could be uttered as a "virtual replica of physical assets intercommunicating in real-time". Therefore, considering its definition, three main components of DTs can be recognized as the physical counterpart, the virtual counterpart, and the connection between them [84,85]. Among the sectors that benefit the most from DT implementation are manufacturing [86], building and construction [28], urban planning and smart cities [87,88], supply chain management [89,90], and health care [91].

In the built environment context, DT has evolved as an exhaustive approach to plan, predict, manage, and demonstrate the assets. Consequently, it can provide the industry with benefits in terms of efficiency, safety, reliability, security, innovation, maintenance decision-making, and lowering costs, risk, and design time [92–95]. Thus, DTs aim to synchronize the real world with a virtual model for seamless administration and control of the construction processes, environmental monitoring, infrastructure solutions, and lifecycle operations [96]. Due to their information-driven nature as well as the ability to replicate the behavior of physical assets, DTs offer cost-effective solutions for simulation and process emulation, where different probable scenarios in the asset lifecycle can be appraised just through the digital model, and without disturbing the real-world performance [97,98].

Characteristics, Scope, and Challenges

Connectivity is the core element in smart systems and a critical requirement of DTs for data fusion and preprocessing of Big Data to improve the designed systems and ultimately enhance data integration and exchange, maintenance and safety, operation risk mitigation, energy management, and real-time automated optimization in the built environment [99,100]. Connectivity is also the joint characteristic of DT and IoT, spotlighting the integration of these two technologies [101,102], which will be discussed further in this article. Merging a building DT with its physical counterpart to structure and access data from different sources including simulations and IoT, Grübel et al. [103] have even made use of augmented reality (AR) in their demonstrated prototype as the first step toward an AR media architecture.

Self-evolution is also an attribute of DTs, which implies their capability to alter and adapt in response to actual circumstances. Because of the ability to realize intuitive observations as well as predicting the working state, and also thanks to self-evolution and interactive feedback, as their two key characteristics, DTs offer the potential to handle operation and maintenance activities in a more efficient, intelligent, and timely manner [84,104,105]. In this respect, Zhao et al. [7] tried to address the challenges such as misalignment in data integration and data standards in the implementation of DT as a support means concerning facility management over the building operation and maintenance phase. In their study, they have developed a bottom-up conceptual framework, through an illustrative case-study approach.

Furthermore, fidelity is another feature of DTs, which in the literature is referred to as the level of accuracy in which the virtual replica reflects the physical counterpart [106]. Fidelity also directly depends on the number of parameters exchanged between the virtual and physical entities and their level of abstraction of reality chosen for the virtual replica [85,92]. Therefore, it follows that a higher level of fidelity can ensure a closer alignment between the physical counterpart and the virtual replica. Nonetheless, even assuming full data acquisition, there may still be other challenges regarding high fidelity such as data storage management, computational processing power, data transfer limitations, and turnaround time for decision support.

Boje et al. [28], characterizing three generations for DTs in building construction, proposed an evolutionary three-tier paradigm. The first generation refers to monitoring platforms, which as the preliminary effort in DT, enable physical sensing with a limited degree of analytics and reporting. This step is a boosted version of the current BIM on construction sites. The second generation, on the other hand, indicates intelligent semantic platforms, which are in fact enhanced monitoring platforms with some degree of intelligence. Hence, in this step, a knowledge base is formed through deploying a common web-language framework to represent the DT together with all the integrated IoT devices. Eventually, agent-driven socio-technical platforms, as the third generation of DTs (and at the pinnacle of possible DT performance to date), characterize fully semantic DTs, exploiting attained knowledge through AI-powered agents. The techniques required to establish a self-learning, self-updatable, and self-reliant DT include data mining, machine learning, and deep learning.

Exploiting the virtue of DTs for built asset monitoring and anomaly detection in building operations and maintenance is significantly noted in the literature (e.g., [107–110]). With a predictive maintenance approach, DTs try to understand the past and present functionalities of the asset to provide the basis for prediction of the future behaviors and make the due decisions accordingly [28,107,111]. To deploy a functional predictive maintenance scheme for automatic fault detection and diagnostics in the building heating, ventilation, and air conditioning (HVAC) systems, three major elements are recognized by Hosamo et al. [112], viz., (1) Big Data collection from ambient sensors, which are necessary to learn how the equipment operates; (2) a platform to execute automatic fault detection and diagnostic algorithms and infer how to better the maintenance systems and predict the failures; (3) BIM models for data transfer and 3D visualization.

Despite all the potential that DTs bring to the industry, its implementation, specifically in the building industry as a highly fragmented sector, also comes with notable challenges. Shahzad et al. [113] investigated such challenges and divide them into three categories, namely data security and ownership, lack of common data standards and tools, and diversity in source systems. Addressing these challenges, among other things, demands clarifying roles, responsibilities, access levels, regulations, resources, tools, and techniques.

Table 4 summarizes the research focus and outcomes of the retrieved studies pivoting around the implementation of DTs in the building industry.

Table 4. Literature on DT implementation in the building industry.

Reference	Year	Research Focus Utilizing Digital Twins	Outcome
Lu et al. [107]	2020	Anomaly detection, operation and maintenance, asset information management	An IFC-based structure, monitoring asset conditions extracted from DT
Pan and Zhang, [14]	2021	BIM, data mining, time series analysis, handling large BIM data, project management	An integrated DT framework
Hosamo et al. [112]	2022	Facility management, fault detection, predictive maintenance, HVAC operation,	A DT predictive maintenance framework for air handling units
Ogunseiju et al. [100]	2021	Ergonomics, wearable sensors, augmented reality, deep learning,	A DT framework to enhance self-management ergonomic exposures
Lee and Lee, [114]	2021	Modular construction, BIM, GIS, real-time logistics simulation	A DT framework to predict the logistic risks
Wahbeh et al. [115]	2020	Virtual design and construction, BIM, IoT, analysis of DT concepts	Proposing and employing the DT concept as a goal for a project-based learning strategy in a didactical setting
Lin et al. [94]	2021	Building modeling, hybrid models, zero energy building, capturing the dynamics of physical entities	A hybrid approach to creating DTs combining physics-based and ML methods
Tagliabue et al. [105]	2021	Sustainability assessment systems, BIM, real-time control and assessment of sustainability criteria	A DT-IoT framework for enabling dynamic sustainability assessment
Greif et al. [90]	2020	Decision support system, supply chain management, smart logistics	Developing a silo dispatch and replenishment decision support system
Sun and Liu, [96]	2022	Real-time data management, transform and store Big Data collected by sensors, IoT, DT-BIM	A hybrid algorithm integrating BIM and DT.
Gardner et al. [111]	2020	Data-driven modeling, machine learning, predictive capabilities of DTs	A DT model merging physics- and data-based modeling
Zhao et al. [7]	2022	Facility management, BIM, enhancing collaboration and information communication over the project lifecycle	A DT conceptual framework to enhance facility management

4.3. *IoT—The Spirit of the Smart Built Environment*

The International Telecommunication Union (ITU) [116] defines IoT as "a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies." IoT is being implemented in various fields and sectors including asset tracking, health care, resource management, smart buildings, and smart cities, while various technologies such as wireless sensor network (WSN), radio frequency identification (RFID) and the like can be used depending on the use case [117–119].

As mentioned earlier, the connectivity between the physical asset and its virtual representation is the third main pillar in DTs, where IoT is deemed to be a key enabling technology [114,120,121]. IoT serves as a channel that allows contextual data transmission from the users to DTs and facilitates smoother interaction between the users and the ambient environment [122]. As a relatively nascent yet promising technology [123,124], IoT is expected to smarten the built environment by bringing billions of various devices online over the next few years [125,126]. It aims to improve construction operations, mitigate waste, and enhance savings in the building industry [127]. Miller et al. [128] introduce the concept of Internet-of-Buildings (IoB) outlining the creation and testing of a platform to aggregate data using IoT and wearable technologies for bettering the connection with BIM and GIS. Furthermore, construction companies could also take advantage of IoT sensors to boost the performance of their equipment [129].

Nonetheless, IoT implementation also has its challenges, some of which are the high investment cost, data security and integrity concerns, technology and communication infrastructure demands, and immaturity of IoT standards [130]. On the other hand, processing the massive amount of data collected through IoT sensors demands a far more efficient IT infrastructure than the existing cloud-based systems [131] to conduct micro value exchanges automatically while maintaining the security of the data. When it comes to handling Big Data, a remarkable deficiency of these systems is the dependency on the centralized data architecture as a single point of failure [132], when the data are gathered from all the connected devices, processed in the central cloud, and sent back to those devices to align them [133]. Such a centralized communication model impedes the swift transmission of real-time data and large-scale data processing, where Deng et al. claimed that blockchain technology can be considered a proper solution [134].

Integration of IoT with blockchain, as an outstanding technological paradigm shift, can effect considerable changes in the contemporary smart built-environment [3], as individual components and assets can directly communicate over a huge network and smartly provide self-sustaining services. Through decentralization of IoT networks, blockchain technology could provide a solid bedrock for bringing the online devices into alignment peer-to-peer [135], sharing the resources [136], processing the data and making the decisions locally [78,137,138], while avoiding the centralized system security weaknesses and vulnerabilities [139]. Moreover, the combined use of blockchain and IoT can also cultivate innovative and efficient systems, especially with smart contract implementation for autonomous decision-making [140,141], to overcome issues regarding security, interoperability, and connectivity, which are indexed as the crucial challenges for the effectivity of IoT for the interconnected devices [140]. IOTA, as a distributed ledger, specifically developed to capture and process data from IoT devices and sensors, is an attempt in the same respect, which also surpasses conventional blockchains by offering advantageous features regarding scalability, being fee-less and quantum-resistant [69].

Table 5 summarizes the research focus and outcomes of the retrieved studies pivoting around the implementation of IoT in the building industry.

Table 5. Literature on IoT implementation in the building industry.

Reference	Year	Research Focus Utilizing the Internet of Things	Outcome
Han et al. [124]	2022	Compaction quality monitoring and management, road construction industry, BIM	A BIM–IoT framework and prototype for informationized management and visualization of road construction
Desogus et al. [142]	2021	Building consumption and indoor conditions data monitoring, energy retrofit, BIM, DTs	Developing, testing, and analyzing an integrated BIM–IoT data platform.

Villa et al. [126]	2021	Monitoring building facilities in the operation and maintenance phase, predictive maintenance, fault detection, HVAC systems	A digital framework for the integration of IoT and BIM platforms
Miller et al. [128]	2021	Adoption of IoT and wearable technologies to aggregate data and establish a better connection with BIM and GIS	Integrating dynamic IoT data from wearables and other sources into GIS and BIM platforms.
Lieberman et al. [25]	2017	Underground urban infrastructure, Big Data analytics, technical and policy challenges, cost-effective and scalable solutions	Exploiting IoT principles for functional DTs of underground infrastructures

4.4. AI—The Industrial Automation Arrowhead

The intelligence demonstrated by machines, referred to as artificial intelligence, is a computational framework that enables computers to make sense of data and learn from them to offer solutions in complex circumstances [143]. Focusing on computer programming and development, AI can enable machines to perform different tasks in the same way as humans or even more efficiently [144]. As a highly advantageous tool in almost all industries, AI makes it possible to increase the speed and accuracy of process completion, avoiding human errors, reducing common risks, and enhancing efficiency.

Machine learning (ML) and deep learning (DL) are the subsets of AI that can provide the building industry with benefits such as improving the quality of designs, creating a safer job site, assessing and mitigating risks, and enhancing asset facility management [145–148]. The insights gained can also improve decision-making and strategy development for construction management on a large scale [149]. They can also overcome the hindrances of IoT networks through identifying patterns and anomalies, and making predictions based on the large amount of data accumulated by devices and sensors in the IoT network [150]. The potential of AI throughout the planning and design phase is an improvement in the accuracy of cost estimates and a decrease in onsite risk using constructive alternative analysis. In the same way, the advantages of AI in the construction phase include bettering work procedures, enhancing productivity, and lowering the risk of onsite accidents [151].

AI is increasingly being employed in different contexts to enhance productivity through improving decision-making and streamlining workflow [45]. Implementation of AI and ML techniques together with DT provides a solid substructure for increasing the whole facility management system intelligence as well as establishing a rigorous communication network between the stakeholders interacting with the asset real-time status [7]. Although AI, as a smart computational technique performing intelligent predictions, recognitions, and actions, can enable machines to learn autonomously by processing different data sets and making sensible decisions [1,152], it lacks the ability to maintain the integrity of the prediction result and therefore needs external authorities for ensuring the system security [153].

On the other hand, as already outlined, blockchain can ensure a transparent and immutable digital record of transactions by maintaining it on a peer-to-peer network, while it also establishes trust between anonymous transacting parties without the need for any intermediaries [8]. In fact, it provides the consensus on digital distributed ledgers, shared between scattered nodes in an untrusted environment, whilst the access control over the electronic records and systems is well assured [1]. Nevertheless, blockchain, which offers a static smart contract to handle decentralized transactions, lacks the capability of dynamic decision-making [153].

Therefore, AI and blockchain could complement each other, and their combination, as two of the most leading-edge technologies, promises a great breakthrough in the industry [1,152,154]. Such a synthesis will ensure data quality as well as overcoming risks such as human mistakes and hacking [109,155]. Hence, AI and blockchain are conceptualized as the "yin and yang" of today's technological revolution, as AI provides the industry with machine-driven recognition, understanding, and decision making, while blockchain technology plays a supportive role in terms of execution, verification, and recording [156]. A practicable instance of blockchain and AI integration is to embed the AI coding in a smart contract to safeguard it through mitigating the risk of code manipulation by unauthorized parties [153]. In this way, inviolable codified laws will be generated, which govern the AI functionality, and at the same time, it would be possible to take advantage of AI to debug smart contracts as well as improving the blockchain's protocol design [45].

Table 6 summarizes the research focus and outcomes of the retrieved studies pivoting around the implementation of AI in the building industry.

Table 6. The literature on AI implementation in the building industry.

Reference	Year	Research Focus Utilizing Artificial Intelligence	Outcome
Zhang et al. [146]	2020	Surveillance of construction equipment and action recognition, computer vision, long short-term memory, and convolutional neural network	Developing a deep learning-based approach for construction equipment action recognition
Agostinelli, [16]	2021	Computer vision, visual building data, predictive maintenance, facility management, smart cities, GIS	Integrating AI and city digital twin model to support security and facility management
Regona et al. [151]	2022	Big Data analysis, automation, robotics, social media analytics	Content and sentiment analyses of location-based Twitter messages
Kochovski and Stankovski, [109]	2021	Cloud-to-edge computing, blockchain, IoT, the DECENTER Fog Computing and Brokerage Platform	Utilizing DECENTER addressing requirements for flexible implementation of AI methods in construction projects
To et al. [108]	2021	DT information augmentation, real-time applications of AI in the building industry, unmanned aerial vehicles	An AI-driven information fusion framework in order to augment DT in buildings
Wu et al. [95]	2022	Real-time hazard awareness, safety risk information presentation for construction sites, mixed reality, DT, DL	A visual warning system for workers' risk assessment on construction sites

5. Technology Fusion

The concept of technology fusion or technology convergence refers to the integration and transformation of two or more different core technologies in an innovative manner to create new growth potential for the industry, while being both complementary and cooperative, are the key features of this phenomenon [157,158]. Instances of technology fusion include, but are not limited to, hardware–software fusion, computing–communication fusion, cloud or distributed computing, and fusion between virtual and physical reality [159].

As it emerged from the literature search results, IoT and AI are among the technologies most associated with the integrative implementation of DTs and blockchain [160], having the capacity of improving them and addressing their challenges. This section offers a brief inspection of the functional scenarios and use cases in the literature to date, in which the highlighted disruptive technologies are integrated to put forward promising solutions for inherent challenges of each technology as well as those of the building industry.

The Scholarly Records in the Building Industry

The integration of DTs and blockchain technology in the built environment has gained great traction of late. Blockchain makes it possible to store information from DTs in distributed ledgers, facilitates interaction between DTs, and allows them to enter into smart contracts. Information sharing, security and integrity, real-time data analysis, and prediction are the aspects that highlight some of the advantages of such technology fusion powered by data analytics technologies [161].

Discussing DT capacities through different industrial use cases and case studies, Yaqoob et al. [34] highlighted major barriers as well as key benefits to the adoption of blockchain in DTs. Tezel et al. [62], with a similar attitude, offered a conceptual framework clarifying the possibilities of adapting construction supply chains to benefit from blockchain. For this purpose, they took a SWOT analysis approach based on the views of the key players in blockchain-enabled construction. In like manner, Götz et al. [162] developed a model of framework exploring the blockchain-based DT potential in terms of applicability, interoperability, and integrability for asset lifecycle management. They found this technological synergy a promising strategic construct, while providing multifunctional on-field support. In this study, organizational prerequisites are underlined as important considerations in adapting such integration at the industry level.

Beyond such theoretical arguments that lead to the development of conceptual frameworks, some studies have attempted to practically examine the integrability of blockchain and DTs in different contexts. For instance, Putz et al. [12] introduced the EtherTwin DApp prototype, as an owner-centric decentralized model for DT data sharing among the untrusted parties over the asset lifecycle, while ensuring integrity, confidentiality, and availability. Furthermore, employing blockchain and IoT in a smart product-service system, Li et al. [78] developed a service-oriented smart platform facilitating interactive innovation of prefabricated housing construction stakeholders. Herein, prefabricated components are defined as smart connected products to adapt a platform-enabled approach. In this platform, blockchain as a distributed security technology is considered a means of sparking new modes of smart construction. Lee et al. [6], to support accountable information sharing in a pragmatic manner in construction projects, developed and tested a blockchain-based DT framework ensuring data communication traceability. In this framework, DT via IoT sensors keeps the BIM models up to date in near real-time, whilst blockchain ensures the data transaction authentication.

Leveraging blockchain and BIM for DTs in a highway construction project as the case study, Celik et al. [163] proposed the implementation of smart contracts to enhance the collaboration between different stakeholders as well as handling the tasks and processes. In this study, blockchain is also seen as real evidence distinguishing various roles and responsibilities, particularly when disputes arise concerning file sharing and the operated actions. With a comparable approach to utilizing smart contracts, Hasan et al. [74] also proposed a DT creation process based on blockchain to ensure that data provenance and transaction will be treated in a decentralized, secure, traceable, and immutable manner, deploying Ethereum smart contracts in a private blockchain platform. In their work, they employ smart contracts to control and monitor actions taken by the participants in the DT creation process, and as a result, they propose a generic solution that may be tailored to meet the requirements of any sector.

Twinchain, as a quantum-resilient blockchain solution for efficient DT data management, is a rather different approach for the integration of DTs and blockchain, introduced by Khan et al. [83]. The authors proposed implementing blockchain instead of cloud or fog for reliable and secure DT data management, and claim that Twinchain as a new variant of blockchain enables instant transaction confirmation to tackle the problem with transaction confirmation delay in conventional blockchains. Moreover, due to benefiting from hash-based digital signatures, it would be resistant to quantum computer attacks, which is a point of vulnerability of classical blockchain systems. In somewhat similar research, Shahid et al. [82] attempted to address the same issue regarding blockchain quantum susceptibility by introducing DL-for-IoT as a quantum-secure integration of blockchain with IoT environments. The core technique design in this method is a one-time signature scheme, which significantly reduces the signature size and its creation time compared to common alternatives.

As another instance of such practical endeavors, Hunhevicz et al. [8], by proposing the adaptation of smart contracts to DTs, took advantage of blockchain technology to facilitate performance-based payment execution. To this end, they introduced a technical architecture for blockchain–DT connection to ensure trust and transparency through smart contracts and then corroborated the developed concept through integrating the public permissionless Ethereum blockchain into the digital models. An ultimate objective of their work was to actualize the potential paradigm of the 'built environment as a service'. BlockIoTIntelligence is also an AI-driven blockchain-enabled IoT architecture, proposed by Singh et al. [30], in order for efficient Big Data analysis. In the qualitative assessment of the proposed architecture, the authors explain the implementation of Blockchain and AI in IoT systems with both blockchain-powered AI and AI-powered blockchain approaches. Furthermore, through quantitative analysis, they evaluated the BlockIoTIntelligence architecture performance to collate the research already conducted on the cloud, edge, fog, and device intelligence in terms of accuracy, security and privacy, latency, computational complexity, energy cost, and such like.

Lokshina et al. [164] presented a system design to integrate blockchain, as a means of security and control, into BIM and IoT in the case of a smart museum. However, they assumed that the proposed design was generalizable to various types of private and public buildings to establish an innovative framework for digital transformation and enhance data security, building efficiency, and the safety of humans and assets. In a similar attempt, Rane and Narvel [79] developed a Blockchain-IoT integrated architecture to enhance the agility of the project resource management process in the engineering, procurement, and construction industry. The introduced architecture was intended to offer contributions to, among others, real-time data acquisition as well as autonomous resource coordination with the expanded capability of decentralization, handling trustless transactions, transparency and security, as the key drivers for enhanced process agility.

Decentralizing the AI applications is seen as the next wave of blockchain implementation by Adel et al. [1]. In their research, they offered a tailorable blockchain-based AI system as an inference engine to validate and audit the decision-making process; enable distributed AI repository configuration; provide a functional solution for the distribution problem in the AI applications; and ensure sustainable versioning and evolution for AI applications in the construction industry. Furthermore, benefiting from the convergence of BIM, blockchain, and IoT in the built environment, Siountri et al. tried to explore the applicability and interoperability of such technology fusion by introducing a system architecture in their research, where management, monitoring, and security were considered critical factors for the smooth functioning of the host organization [80,81].

Although the research on the fusion of the discussed technologies is in its infancy, valuable efforts have already been made in this field, some of which are referred to in this section. However, some of them have much room for further elaboration on their methods and can be developed in the implementation details. Indeed, it is also asserted in many studies that these emerging technologies need to grow to a higher level of maturity [3,74] to be fully implementable and provide secure and scalable real-world solutions.

6. Discussion

The integration of disruptive digital technologies in the building industry is a kind of radical innovation, which demands a collaborative initiative in business relationships to form a unified digital ecosystem, allowing firms to manage and regulate a building project lifecycle in a timely manner [165]. An overview of the recent literature distinguishes IoT and AI as the most advantageous technologies to enhance blockchain-based DTs and their efficiency in the building industry. IoT is characterized as the most important pillar of DT to keep it updated with real-time data, while AI brings intelligence and recognition power to the DTs and facilitates activities such as anomaly detection and predictive maintenance [112]. On the other hand, AI and blockchain are considered complementary technologies [156], the combination of which can ensure the improvement of smart contracts and bring data security into DTs, while blockchain can facilitate and secure the local computing in IoT networks [166], benefiting from the capacity of individual nodes instead of relying on centralized cloud-computing solutions.

Considering the enhancement of the smart and sustainable built-environment as the ultimate goal, this study has quantitatively and qualitatively reviewed the recent research by adopting an analytical approach to better comprehend the identified disruptive technologies, their interfaces, and their potential to redress each other's deficiencies. The bibliometric scrutiny of the publications reveals the increasing trend in research on such innovative technological synergies, while inspection of the characteristics of the technologies and their fusion implies that the capacity in this sphere is huge.

6.1. An Abstract Body-Like Model of Technological Synergy

The inspection of the highlighted technologies, their capabilities, and the ways they can be integrated, underlined in the reviewed literature, reveals that the configurative and synergistic form of their fusion is comparable to the way that the human body functions biologically. If DT is assumed equivalent to the body, AI, IoT, and blockchain will play almost the same roles as do the brain, the circulatory system (blood vessel network), and the nervous system in the body, respectively. In other words, DT can implement the other technologies in the sense that the body employs the organs, while the activities such as anomaly detection in the asset are commensurate with the purposeful physical activities of the organs.

Smart and purposeful activities require to be directed by an intelligent decision-maker. This highlights the role of the brain/AI in this analogy. The brain enforces its commands throughout the body through a distributed organ, which is the nervous system. Similarly, AI's decisions can also be legitimized by blockchain, as a decentralized network, and executed on DTs. The executive interface for such enforcement in the body is the spinal cord, which can be presumed to be equivalent to smart contracts in this abstract model. Having this analogy drawn, the complementarity of AI and blockchain can be better understood.

IoT has the same function as the circulatory system, in the sense that it feeds the body of DT with information and keeps it up to date by pumping real-time data. Just like the circulatory system (arteries and veins) that flows blood in both directions, to and from the heart, the IoT data are also transmitted both from individual devices on the network to the central cloud, for being processed, and in the reverse direction, for providing feedback. Here, the centralized cloud computing platform plays the same role as does the heart in the body. In this model, the interconnection between IoT and AI can also be explained in such a way that just as the brain is fed by blood in the circulatory system, artificial intelligence uses the raw data provided by the IoT network as its learning materials.

Nevertheless, the technology fusion model, portrayed in this section, has potential beyond the body's biological function pattern. Unlike the nervous and circulatory systems in the body, blockchain and IoT networks have the opportunity to merge. As a result, the conventionally centralized intelligence can be spread throughout the entire system, leveraging the processing power of individual nodes. Moreover, data from IoT devices will be processed locally with no need to be transmitted back and forth between the devices and the centralized cloud computing platform. Benefiting from such advantages, the single point of failure, which is one of the most outstanding weaknesses of conventional systems, could be avoided as in blockchain networks the failure of a single node will not paralyze the whole system. Assuming that the body was also able to biologically merge its nervous and circulatory systems in a similar way, the risk of stroke and heart attack would be completely avoided, as the brain and heart are in fact instances of a "single point of failure" in the body.

6.2. Research Gaps and Future Directions

As the review results assert, the synthesis of the discussed technologies is very nascent, yet exponentially increasing and gaining great traction in both academia and industry. Nevertheless, some substantial gaps in the research are quite evident. First of all, the variance in the conceptualizations and the definitions of the fundamental concepts in the reviewed literature are sometimes confusing, which underlines the necessity of a comprehensive international consensus on the concepts [115]. Moreover, to the best of the authors' knowledge, no research has investigated the interactive fusion of all these four technologies to form a unified system architecture. However, a large number of studies have recently been focusing on the integration of two or three of these technologies (see Appendix A). On the other hand, very little research has implemented practical methods, and most of them are just limited to theoretical discussions leading to the development of conceptual frameworks. This gap is particularly evident when it comes to the implementation and integration of blockchain technology, while it has also not yet been well established, neither in research nor in practice, partly due to the lack of public awareness of its quiddity and benefits [138]. Therefore, more empirical case studies are required to assess and validate the functionality of theoretical models. Furthermore, the technical details of the implementation and integration of technologies are usually not clearly elaborated in studies that adopt and follow practical methods. Hence, future research should focus on the integration of these technologies by developing practicable systems and functioning prototypes that handle real-world real-time data in the built environment in a coherent manner and deliver tangible results [49]. Indeed, the simultaneous implementation of these technologies requires specialized service providers to adopt one-stop-shop solutions, which is also another considerable challenge. In this regard, encapsulating the technological complexities and providing more user-friendly interfaces can also be significantly effective in the proliferation of such technology fusion approaches in the industry.

Figure 10 exhibits a visual summary of the study, the Venn diagram on the left side of which provides a quantitative insight into how the focus of the literature is distributed over different technologies. For instance, 15 studies address just blockchain in the building industry, while 11 investigated both blockchain and IoT. By adding up all the numbers nested in the yellow oval, it can be inferred that 43 studies have considered blockchain (either independently or in integration with other technologies). As also illustrated in the figure, each technology faces challenges that can, to a large extent, be overcome when they are integrated. The potential benefits of technology fusion to address some of those challenges are listed in the boxes, where the arrowheads meet, and the detected gaps in the literature are briefly summarized followingly.

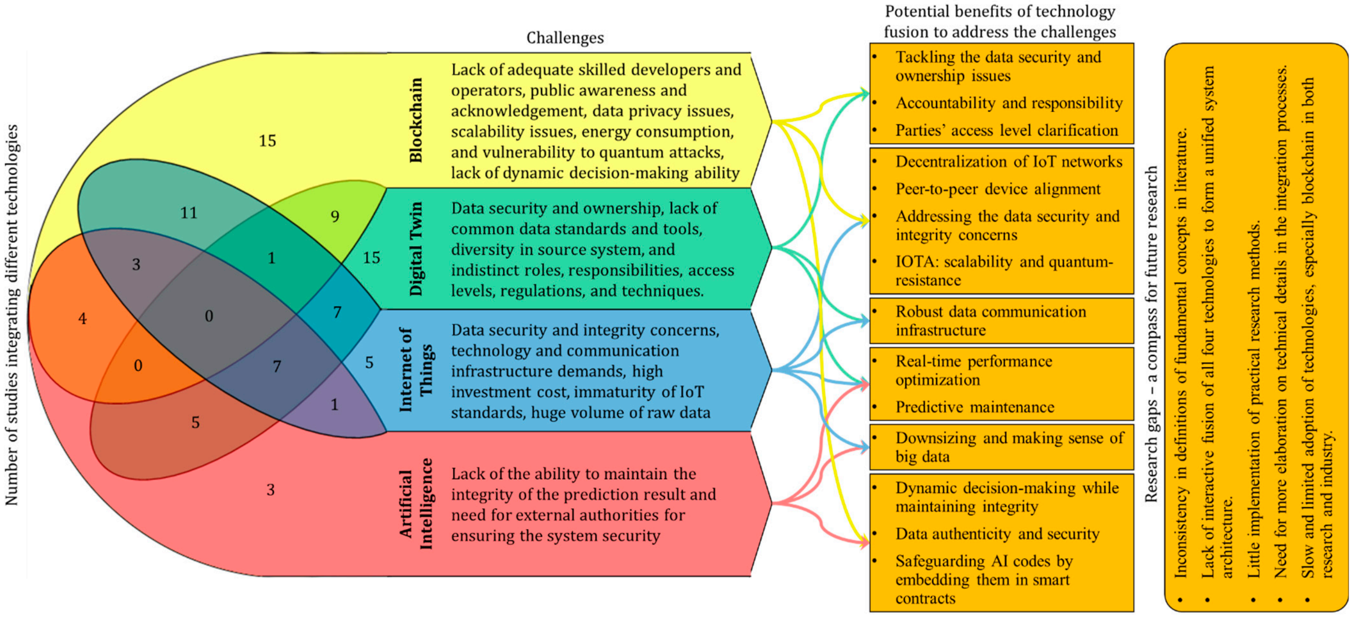

Figure 10. A visual summary of the study.

7. Conclusions

Towards the goal of exploring the trend and evolution of the integration of disruptive technologies in the building industry, this study reviews the literature in the last five years focusing on blockchain, digital twins, and the enabling technologies for enhancing their integration. In the first step, through a preliminary literature search, AI and IoT were recognized as the two top enablers. Then, by formulating search strings combining the identified keywords, the main query was conducted. The search led to the retrieval of 86 papers after evaluating inclusion and exclusion criteria, elaborated in the research method section.

As a next step, a bibliometric analysis of the retrieved literature provides a statistical insight into the co-authorship, co-occurrence of keywords, citations, and bibliometric coupling of the sources, followed by the elucidation of the fundamental concepts in each technology as well as their challenges and potential for integration with each other. The outcomes indicate that the integration of these technologies is in its early stages demanding more scholarly research and contribution from the industry. Nevertheless, such a fusion of technologies opens the door to overcoming the deficiencies and challenges in their implementation. In the end, drawing an analogy between the technological synergy and the human body, this study offers an abstract body-like model to facilitate the understanding of the role and benefits of each technology in their integration.

Furthermore, the study emphasizes the need for interdisciplinary collaboration between researchers and practitioners in the building industry, as well as other various technological fields. Therefore, it is crucial for professionals in the building industry to be aware of the latest advancements and trends in these technologies and their integration to stay ahead in a rapidly changing landscape. This consideration of new and innovative solutions, such as the applicability and fusion of disruptive technologies, also acknowledges the novelty of the research and paves the path for the upcoming practical and empirical studies.

Although the present review has tried to cover as many key concepts and subjects as possible around the investigated technologies, it was limited to the building sector. Therefore, the way that other industries take advantage of these technologies can be very inspiring for researchers and practitioners in the built environment. The reviewed documents have also been limited to the ones indexed in the Scopus and Web of Science databases, which is another limitation of this study. However, this restriction can, on the other hand, guarantee the scientific quality of the considered literature, as these databases are among the most credible scientific search repositories.

Finally, the scope of this study is limited to the technical aspects of implementation and integration of technologies, while many other decisive factors such as the regulatory and social aspects should be taken into consideration. These perspectives are especially highlighted in blockchain adoption, as it is seen as a transformative factor in social infrastructure and demands novel approaches, regulations, and administrative policies at national and international levels.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15043713/s1, Table S1: Checklist [167].

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Appendix A. The Retrieved Literature and Their Summary

Reference	Year	Source Type	Identified Challenges	Implemented/Discussed Key Technologies				Research Objective(s)	Proposed Solution(s)
				Blockchain	DT	IoT	AI		
Adel et al. [1]	2022	Journal	Lack of research regarding blockchain and AI that address construction applications.	X			X	Supporting AI decision verification, confidential data sharing and ownership traceability and upgrading of AI models.	Introducing a decentralized AI system within blockchain network.
Agostinelli, [16]	2021	Book chapter	Questionable effectiveness of current surveillance systems and real-time intervention.		X	X	X	Taking advantage of computer vision for more efficient interpretation of visual building data.	Integrated framework involving AI and city digital twin model to support security and facility management.
Aleksandrova et al. [165]	2019	Journal	The challenges of employing new technologies along with BIM in the built environment.	X		X		Examining the modifications brought about by cooperative innovations in business partnerships formed during the period of digitalization in the Russian Federation's construction industry.	Presenting a model supporting the creation of a digital ecosystem in which the role of government in support of employing new technologies is described.
Al-Sehrawy and Kumar, [106]	2021	Conference	Confusion about the concept and definition of DT.		X			Providing a clear definition about DT along with identifying DT's key features.	Reviewing and analysis of the recent literature.
Alshammari et al. [87]	2021	Conference	Lack of focus on cybersecurity of BIM data.		X	X		Investigating the key cybersecurity practices needed for the built environment.	Highlighting obstacles to the adoption of cybersecurity for DTs enhancing the city standards.

Boje et al. [28]	2020	Journal	Incompatibility of BIM with IoT due to BIM formats and standards which limits BIM integration with semantic web.		X	X	X	Evaluating BIM multifaceted applications during construction phase and their limitations and requirements towards construction digital twin concept.	Shedding light on the previous literature to illuminate the future research direction.
Brandin and Abrishami, [40]	2021	Journal	The barriers caused by transparency, interoperability, fragmented information and Big Data management.	X		X		Exploring how new technologies can be employed to support information traceability platforms to enhance efficiency and reduce cycle times, provide information transparency, and trust to offsite manufacturing.	Proposing a framework for the integration of blockchain, smart contract and IoT in support of information traceability.
Brunone et al. [17]	2021	Book chapter	Lack of coherent integration between the development of the design and production phases.		X	X	X	Exploring how BIM, digital tool applications, and sensitization can support product and asset management	Benefiting from the potential of IoT and AI moving from cognitive to predictive buildings.
Calvetti et al. [168]	2020	Journal	The uncertain knowledge gap regarding what manual tasks would potentially be replaced by automation and digitalization	X			X	Investigating the main barriers/issues for ethical implementation of new technologies and systems for workforce performance evaluation and post processing using AI.	Proposing a process framework involving BIM, AI, smart contracts and electronic performance monitoring.
Celik et al. [163]	2021	Conference	Lack of security and traceability of data shared between different stakeholders.	X	X			Developing a blockchain-based solution for DTs to provide a more reliable, sustainable, trustworthy data sharing system.	Presenting a blockchain-based framework to integrate BIM models in the building design phase.
Cheng et al. [169]	2021	Journal	Lack of systematic review on the current status of blockchain application in the building industry.	X	X			Reviewing the current research on blockchain application in the building industry.	Specifying and categorizing the benefits and challenges of blockchain applications in the building industry.

Cho et al. [61]	2021	Journal	Challenges to collect and benefit trustworthy data.	X		X		Securing reliable information of fine dust management data and improving the accessibility to the information using blockchain.	Designing and developing blockchain network model to provide transparency and reliability in data sharing process for participants.
Deng et al. [104]	2021	Journal	The need for more knowledge on how the underlying enabling technologies support DTs.		X			Specifying how the evolution of BIM to DT in built environment can be facilitated by emerging technologies.	Proposing a five-level ladder taxonomy to classify existing research in the field.
Desogus et al. [142]	2021	Journal	Challenges access to building performance data using IoT.			X		Enhancing building consumption and indoor conditions' data monitoring.	Developing, testing, and analyzing a BIM-IoT integrated data platform.
Elghaish et al. [138]	2021	Journal	Lack of researches evaluating the status que of research in IoT and blockchain in the building industry using scientometric analysis.	X		X		Reviewing and analyzing the existing research concerning IoT-blockchain integration in the building industry.	Providing a taxonomy of topics where blockchain and IoT can offer solutions in the construction industry.
Engin et al. [88]	2020	Journal	Challenges related to radical growth of data availability and the capacity to process the available data in urban management	X		X	X	Improving urban planning and management to follow the current digital revolution.	Providing a transdisciplinary synthesis of the existing opportunities, development, and challenges.
Gardner et al. [111]	2020	Journal	The need to improve predictive capabilities of DTs.		X		X	To investigate how an asset management-validated model as a building block can lead to DT.	Introducing a DT model merging physics- and data-based modelling that supports generating a learning process.
Ghosh et al. [127]	2021	Journal	Lack of investigation on the research streams on applications of IoT in the built environment, based on the active researchers'			X		Developing a roadmap to apply IoT and other digital technologies in the building industry.	Analyzing the research trends and specifying the key drivers for IoT adoption.

			geographical distribution.						
Godager et al. [101]	2021	Journal	Lack of knowledge regarding Enterprise BIM and the need to create best practices for joint transdisciplinary initiatives.		X	X		Providing a definition on enterprise BIM and evaluate research and practice perspective in order to support enterprises to integrate BIM into their processes.	Conducting interdisciplinary collaborative projects where actors play different roles as well as close collaboration between research and practice within integrated use cases combining the relevant technologies and standards.
Götz et al. [162]	2020	Journal	Lack of frameworks to facilitate the integration of emerging technologies with industry's best practice processes.	X	X			Exploring interoperability, applicability, and integrability of blockchain-driven DTs for lifecycle management.	Model of framework which sees DTs in a wider context in the current technologies and management practices.
Gracanin et al. [33]	2019	Conference	Inadequate attention to human factors such as empathy, privacy, and ethics in the smart built environment.	X		X	X	Providing a vison for the new generation of smart built environment in which empathy, privacy and ethics factors play a key role	Proposing a framework that incorporates game theoretic model addressing empathy, privacy and ethics in the smart built environment.
Greif et al. [90]	2020	Journal	The supply process problems and shortcomings of the status quo of bulk silos.		X			Exploring how construction site logistics can benefit from DTs for bulk silos.	Designing and implementing a silo dispatch and replenishment decision support system.
Grübel et al. [103]	2021	Conference	Lack of immersive capacity in screens to keep up with the newer media.		X			Utilizing AR in the media architecture using DT to structure and access data from different sources including simulations and IoT.	Describing a prototype of an AR media architecture to fuse a building DT with its physical counterpart.
Han et al. [124]	2022	Journal	The challenges to fully employ the potential of Intelligent compaction.			X		Supporting intelligent compaction for advanced quality monitoring and management in the road construction industry.	Introducing an integrated BIM–IoT framework and developing a prototype system as an implementation of the framework.
Hasan et al. [74]	2020	Journal	Deficiency of DT creation approaches and technologies to provide	X	X			Introducing a DT creation process in a trusted, secure and transparent manner, ensuring immutability of	Framework for creating DTs based on blockchain.

			trusted data provenance, traceability and audit as well as tamper-proof data concerning transactions and logs.					transaction, data provenance, and logs.	
Heaton and Parlikad, [11]	2020	Conference	Limitations in adoption of BIM over the asset operation and maintenance phase		X			Investigating how BIM models can be integrated and form an AIM relational database and creation of DT eventually.	Illustrating the development of a single 3D model to integrate multiple BIM models based on West Cambridge campus case study.
Hosamo et al. [112]	2022	Journal	Lack of standardized fault detection process in HVAC operation due to high cost and low flexibility of fault detection methods.		X	X	X	Addressing the limitations of current building facility maintenance management systems.	Offering a DT predictive maintenance framework for air handling unit (AHU)
Hunhevicz and Hall, [2]	2020	Journal	Technical knowledge gap between the use-case ideas and the technical implementation of blockchain.	X				Investigating the researches and use cases in blockchain and analyzing the design options.	Integrated framework to match the characteristics of a use case with blockchain design options
Hunhevicz et al. [8]	2022	Journal	The limitations of performance-based contracts due to challenges such as accountability, financial concepts, and performance evaluation.	X	X			Paving the way for servitization of the built environment through integration of blockchain and DTs.	Prototyping a full-stack architecture integrating the Ethereum blockchain together with the Siemens building twin platform to support performance-based payments.
Khan et al. [83]	2020	Journal	Lack of a commonly accepted narrative of digital twin	X	X	X		Integrating blockchain and DTs to enhance manufacturing processes	Presenting a spiral DT framework which is able to help researchers to form a common narrative about DT as well as proposing a quantum-resilient blockchain model in order to efficiently manage DT data.

Kochovski and Stankovski, [109]	2021	Journal	Lack of comprehensive methodology to apply fog computing to the construction projects.	X			X	Assessing requirements for flexible implementation of AI methods in the construction projects.	Utilizing DECENTER Fog Computing and Brokerage Platform and developing a relevant methodology.
Konikov and Roitman, [148]	2020	Conference	Issues in combination of relational application of specific technologies as well as their economic aspects.		X	X		Investigating where to benefit from new IT technologies in construction industry, and how they can help the industry.	Recommending integration of IoT, Big Data, and cloud computing as a chain of new IT technologies.
Lee and Lee, [114]	2021	Journal	The impact of schedule deviations on the logistic process of modular construction.		X	X		Enabling real-time logistics' simulation for modular construction process	Proposing a DT framework in order to predict the logistic risks and arrival times.
Lee et al. [6]	2021	Journal	Fragmentation between construction industry stakeholders that causes delays and inconsistency in data sharing as well as depriving accountability for project.	X	X			Supporting accountable information sharing in construction projects by integrating blockchain and DTs.	Introducing a framework for integration of digital twin and blockchain.
Li and Kassem, [49]	2021	Journal	Shortage of systematic reviews regarding the application of blockchain and smart contracts in construction sector.	X				Exploring blockchain and smart contract papers with the focus on design, construction, and operation of built assets.	Categorizing the major blockchain applications in construction into eight themes and identifying the gaps.
Li et al. [29]	2019	Journal	Low productivity, poor compliance and regulation, as well as weak payment practices, lack of sufficient information sharing and collaboration in construction industry.	X				Analyzing the existing status of DLT within built environment,	Implementation framework consisting of DLT four-dimensional Model (social, technical, policy, and process) and DLT Actors Model

Li et al. [32]	2021	Journal	The reluctance of production parties within off-site housing production sector to provide data. The operation records can be easily tampered with. The difficulty to track the responsibilities through the operation records.	X				To trace the responsibility in off-site modular housing and make the operation records tamper-proof.	Developing a two-layer blockchain-powered supervision model
Li et al. [78]	2021	Journal	The need to cope with poor interoperability among different stakeholders, insufficient traceability and visibility of real-time data within prefabricated housing. construction (PHC)	X	X			Boosting sustainability of prefabricated housing construction taking advantage of smart product-service systems.	Developing an intelligent platform to support prefabricated housing construction using blockchain and IoT.
Lieberman et al. [25]	2017	Conference	Technical and policy challenges in underground infrastructure data management.	X	X			Offering cost effective and scalable solutions regarding the increasing underground built environment complexity and instrumentation.	Exploiting IoT principles as the best opportunity to work towards functional digital twins of underground infrastructures.
Lin et al. [94]	2021	Conference	Limited research concerning bottom-up approach in which the digital model captures the dynamics of physical entity.	X		X		Improving the occupants' satisfaction and energy efficiency through recording the dynamic behavior of the building HVAC systems.	Presenting a hybrid approach combining machine learning and physics-based methods in order to create DTs for the built environment.
Liu et al. [56]	2021	Journal	Lack of research on how blockchain-BIM integration contribute sustainable building design and construction.	X				Investigating how the integration of BIM and blockchain can potentially impact sustainable building design in city information management context.	Providing a visual analysis of the relationships between BIM, blockchain, and sustainable building in the context of smart cities.

Lokshina et al. [164]	2019	Conference	The security concerns of implementation of IoT in highly modular environments involving different stakeholders with high inter-dependency to each other.	X	X	Investigating blockchain as a means of securing and controlling the integrated IoT and BIM framework.	Proposing a system design to integrate BIM, IoT and blockchain as well as underlining smart building evolving role in the IoT environment.
Love and Matthews, [170]	2019	Journal	Absence of a clear method by which organizations can realize the benefits of adopting digital technologies and produce the desired values.	X		Investigating the processes of benefit management in order to make financial decisions.	Describing the process of developing a generic benefits' dependency network to visualize the organization of the capabilities, changes, and advantages that must be taken into account before adoption using various cause-and-effect linkages.
Lu et al. [107]	2020	Journal	Lack of comprehensive and efficient approaches and strategies for asset information management in favor of monitoring, detecting, recording and communicating O&M issues.	X		Build asset anomaly detection utilizing DTs.	Presenting an IFC-based structure using monitoring data containing operational diagnostic information concerning asset condition extracted from DT.
Mannino et al. [53]	2021	Journal	Limitations of BIM in facility management due to the lack of data in as-built digital models.		X	Reviewing and recognizing the future needs of BIM and IoT in building facility management.	Recommending BIM–Wireless Sensors Network (WSN) connection as the IoT solution for recording and monitoring the physical condition of buildings as well as environmental monitoring management.
Marocco and Garofolo, [110]	2021	Journal	The need for understanding the applications of disruptive technologies in facility management.	X		Conducting a comprehensive review on the applications of disruptive technologies in facility management context.	Illustrating the future research directions based on the highlighted limitations.

Miller et al. [128]	2021	Journal	Lack of spatial context in built environment as a barrier for adoption of IoT and wearable technologies.		X	X	X	Outlining the creation and testing of a platform to aggregate data using IoT and wearable technologies in order for bettering the connection with BIM and GIS.	Addressing the gaps in the prior research by integrating dynamic IoT data from wearables and other sources into GIS and BIM platforms.
Nanayakkara et al. [38]	2021	Journal	Payment issues in construction industry caused by complex construction supply chain	X				Investigating how blockchain can solve payment-related issues of construction industry	Taking advantage of smart contracts to establish trust between stakeholders.
Ogunseiju et al. [100]	2021	Journal	Lack of knowledge regarding the post-training actual body movement of construction workforce and their performance.		X			Improving self-management ergonomic exposures through the bi-directional mapping between workers' postures and the corresponding virtual replica.	Introducing a DT framework in order to enhance self-management ergonomic exposures.
Opoku et al. [93]	2022	Journal	Lack of knowledge about the adaptation drivers of DTs.		X			Identifying the DT's adoption drivers and classify them to provide better understanding.	Exploring the recent literature to classify the drivers into an integrated typology based on the construction project lifecycle.
Pan and Zhang, [14]	2021	Journal	Handling large BIM data in the current data mining techniques.		X	X		Improving project management processes to facilitate data communication and exploration and provide better understanding, prediction, and optimization in the construction operation.	Proposing an integrated DT framework employing BIM, IoT and data mining techniques.
Perera et al. [31]	2020	Journal	Ambiguity over the potential of blockchain implementation in the building industry.	X				Critical analysis of the potential of blockchain in the building industry.	Mapping between blockchain characteristics, drivers and barriers to highlight the potential applicability.
Putz et al. [12]	2021	Journal	Lack of security and trust between different parties in DT data sharing.	X	X			Tackling the need for decentralized data sharing in DTs.	Owner-centered decentralized data sharing model.

Rafsanjani and Nabizadeh, [102]	2021	Journal	The need to highlight how the spatiotemporal data generated by new technologies can affect operational dynamics of the industry.	X			Reviewing the vision, trends and the challenges for the future implementation of virtual design and construction and DT in the building industry.	Presenting a reference model to illustrate the advantages and applications of virtual design and construction and DT.
Rane and Narvel, [79]	2022	Journal	Lack of integration between tools and applications employed in resource management of heavy construction assets.	X	X		Collecting and identify the project resource management related challenges in engineering, procurement and construction industry.	Presenting an IoT architecture for capturing the real-time data from heavy equipment and an integrated blockchain–IoT architecture providing agility and intelligence in project resource management processes.
Raslan et al. [52]	2020	Conference	Asset management process deficiency	X			Addressing the technological gaps, required for improving asset management processes.	Integration of blockchain in asset management processes.
Regona et al. [151]	2022	Journal	The knowledge gap regarding how AI is publicly perceived, application areas, prospects and existing constraints in the building industry.			X	Investigating AI adoption prospects and constraints in Australian construction industry.	Adopting social media analytics as well as content and sentiment analyses of relevant Twitter messages.
Rejeb et al. [171]	2021	Journal	Deficiencies of current database technologies to securely manage and store data	X			Investigating the progress and trends and of blockchain and Smart City research.	Benefiting from smart contracts for numerous trading applications and utilizing machine learning to gain insights from IoT devices.
Sacks et al. [147]	2020	Journal	Combined and optimal use of topological rule inference and machine learning modules for semantic enrichment. Demonstration of BIM models suitable for AI applications, with an			X	Reviewing research and development trends over the past 50 years.	Proposing a framework explaining how different technical, theoretical, commercial and conceptual foundations support the growth of innovation construction tech companies.

			emphasis on machine learning						
Scott et al. [45]	2021	Journal	No challenges, as it is an exploratory literature review.	X				Reviewing the existing research of blockchain in AEC	Presenting 33 application categories into seven subject areas.
Sepasgozar, [99]	2021	Journal	Distinguishing the concept and capacity of DT with the existing computing or virtual models and simulations.	X				Providing clarification over how different DT is from other concepts such as 3D modeling technologies, digital shadows, and information systems.	Probing scientometric analysis and trends to illuminate the state of play and suggestions for future research and application development.
Shahid et al. [82]	2020	Journal	The inability of IoT devices in support of ever-growing ledger size.	X	X			Facilitating the adoption of blockchain and IoT systems through addressing challenges in terms of ledger scalability, light-weight consensus, transaction chaining, and quantum resilient signatures.	Presenting a quantum-secure distributed ledger for IoT systems.
Shahzad et al. [113]	2022	Journal	Lack of knowledge about the concept of DT, characteristics and applications.	X				Analyzing the existing definitions of DT as well as its characteristics, applications and challenges for implementation.	Exploring the merits and the relevance of DTs through a literature review and supporting them with semi-structured interviews.
Shojaei et al. [70]	2019	Journal	Lack of coherent database containing the required supply chain information as well as their traces.	X				Evaluating the potential of blockchain to act as an infrastructure to improve decision making of built asset sustainability.	Highlighting the necessary information for decision making at all phases of the asset lifecycle as well as developing a blockchain-driven model supporting built asset sustainability.
Singh and Kumar, [47]	2022	Journal	Challenges of construction procurement processes and the contractual barriers.	X				Exploring how blockchain and smart contracts support supply chain management in the building industry.	Elaborating blockchain-driven processes for database creation as well as transaction and transfer of rights.
Singh et al. [30]	2020	Journal	Challenges of designing and developing Big Data analytics using artificial	X	X	X		Designing and developing an IoT architecture to support analysis of Big Data	Blockchain-based IoT architecture using AI to provide an efficient foundation for the integration of blockchain AI and IoT.

			intelligence such as security, centralized architecture, resource constraints, and training.					
Singh, [129]	2020	Conference	Security issues with IoT application in the building industry.	X	X		Overviewing IoT-blockchain applications in the building industry.	Revealing and elaborating the blockchain's potential applications integrated with IoT in the construction and infrastructure industry.
Siountri et al. [80]	2020	Journal	The need to embrace digital transformation in the building industry, in terms of security, management, and monitoring.	X	X		Integration of BIM, IoT and blockchain for boosting smart built environment.	Developing a system architecture employing blockchain to securely adapt in BIM-based system that is coupled with IoT.
Siountri et al. [81]	2019	Conference	Security related issues of centralized BIM-IoT systems.	X	X		Examining the interoperability of IoT, blockchain, BIM, and other advanced technologies required in the demanding environment of a museum building.	Proposing a system architecture to advance a smart museum building utilizing BIM, IoT, and Blockchain.
Sun and Liu, [96]	2022	Journal	The deficiency of existing systems to present real-time data, difficulties to transform and store Big Data collected by sensors, the existence of various hardware, user interfaces, and data formats.	X	X	X	Evaluating the performance of DT and BIM and how to support intelligent dispatching system.	Proposing an novel hybrid algorithm using BIM and DT.
Tagliabue et al. [105]	2021	Journal	The inability of sustainability assessment systems to benefit from asset dynamic data instead	X			Enabling real-time control and assessment of a variety of sustainability criteria from a user-centered perspective	Introducing a framework supporting the shift from static sustainability assessment towards a dynamic approach based on DT and IoT.

			of using checklist as a tool.						
Tariq et al. [172]	2022	Journal	Lack of focus in current research on soft computing tools such as AI in the development of solar chimneys and algorithm-based multi-objective optimization for decision-making purposes. Lack of research on the macro and global impacts of solar chimneys concerning economy, environment, social, and political aspects.		X		X	Optimizing the sun-facing wall performance connected to a typical vertical solar chimney for different climate zones.	Developing a DT model of a solar chimney using a multivariate regression model based on AI and the least square method.
Teisserenc and Sepasgozar, [3]	2021	Journal	Inefficiencies, fragmentation of information, and lack of trust over the project lifecycle.	X	X			Implementation of blockchain for DTs in building, engineering, construction, operations, and mining industries.	Developing a conceptual framework to address the key technological factors as well as considering the regulatory and environmental aspects, and the circular economy.
Tezel et al. [62]	2020	Journal	Digitalization gap between large and small companies, lack of trust, privacy and intellectual rights in data sharing between stakeholders.	X				Exploring how construction supply chain can be prepared for employing blockchain.	Proposing a conceptual framework based on the results of a SWOT analysis approach.
To et al. [108]	2021	Conference	The need for DT-BIM integration and the real-time applications of AI in the building industry.		X		X	Enhancing DTs in buildings using AI and 3D reconstruction by enabling unmanned aerial vehicles.	Developing an information fusion framework in order to augment DT in buildings.
Turner et al. [149]	2021	Journal	High complexity in construction projects and		X	X	X	Exploring how industry 4.0 technologies can form and support ‘connected’ construction sites in order to	Implementation of smart wearable devices in the digitally enhanced construction sites.

			low productivity and information management efficiency.					improve efficiency, sustainable practices and worker safety.	
Veuger, [26]	2018	Journal	Instability in the financial markets and consequently the real estate markets.	X			X	To investigate how blockchain technology can enhance real estate economy.	Highlighting real estate entrepreneurship, considering trends and developments throughout time for each real estate sector.
Villa et al. [126]	2021	Journal	Lack of interaction between building models and IoT data.			X		Integrating IoT alert systems with BIM models in order to monitor building facilities in O&M phase.	Proposing a digital framework in support of the integration of IoT and BIM platforms.
Wahbeh et al. [115]	2020	Conference	Lack of research providing clear and unique definition about DT concept.		X	X		Analyzing and clarify the definitions of DT in the building industry.	Establishing DT concepts adapted from other industries to the building industry and investing in basic level education.
Wu et al. [95]	2022	Journal	The need for real-time hazard awareness.		X		X	Improving the safety risk information presentation for construction sites.	Proposing a visual warning system for construction sites.
Xu et al. [36]	2022	Journal	High concentration of current research on construction phase and less research concerning pre-construction and O&M.	X				Studying the current blockchain research and identifying key topics and future research of blockchain in AECO.	Proposing a framework for future research in blockchain in the building industry.
Yaqoob et al. [34]	2020	Journal	Traceability, authenticity, compliance, and safety in DT communication	X	X			To discuss how DT-blockchain integration can reshape manufacturing by providing traceability, authenticity, compliance, safety and quality.	Offering a taxonomy of DTs and highlighting major barriers as well as key benefits to the adoption of blockchain in DTs
You and Feng, [119]	2020	Journal	Challenges in benefiting from new technologies in construction industry and the need for more investigations.			X	X	Improving the overall capabilities of construction management and organization.	Offering a framework for integration of cyber-physical systems whose technological feasibility is confirmed by a case study.

Zhang et al. [146]	2020	Journal	Lack of data set in construction equipment action recognition research.			X	Investigating computer vision capabilities for better surveillance of construction equipment.	Developing a deep learning-based approach combining long short-term memory and convolutional neural network approaches.
Zhao et al. [7]	2022	Journal	Lack of empirical efforts on the potential of DTs in enhancing collaboration and information communication throughout project lifecycle.		X		Performing an illustrative case study comparing practical use cases of digital twin technologies.	Proposing a DT conceptual implementation framework to improve efficiency of facility management.
Zheng et al. [37]	2019	Journal	Lack of works on information security and lack of proposed BIM systems to cope with the new computing paradigms such as mobile cloud computing, Big Data, BC, and IoT.	X			Tackling information security in BIM models and mobile cloud architecture.	Proposing a novel blockchain–BIM system facilitating BIM data audit.

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