

Review

Adoption of Blockchain Technology through Digital Twins in the Construction Industry 4.0: A PESTELS Approach

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Abstract: The key challenges of the building, engineering, construction, operations, and mining (BECOM) industries are the lack of trust, inefficiencies, and the fragmentation of the information value chain into vulnerable data silos throughout the lifecycle of projects. This paper aims to develop a novel conceptual model for the implementation of blockchain technology (BCT) for digital twin(s) (DT) in the BECOM industry 4.0 to improve trust, cyber security, efficiencies, information management, information sharing, and sustainability. A PESTELS approach is used to review the literature and identify the key challenges affecting BCT adoption for the BECOM industry 4.0. A review of the technical literature on BCT combined with the findings from PESTELS analysis permitted researchers to identify the key technological factors affecting BCT adoption in the industry. This allowed offering a technological framework—namely, the decentralized digital twin cycle (DDTC)—that leverages BCT to address the key technological factors and to ultimately enhance trust, security, decentralization, efficiency, traceability, and transparency of information throughout projects' lifecycles. The study also identifies the gaps in the integration of BCT with key technologies of industry 4.0, including the internet of things (IoT), building information modeling (BIM), and DT. The framework offered addresses key technological factors and narrows key gaps around network governance, scalability, decentralization, interoperability, energy efficiency, computational requirements, and BCT integration with IoT, BIM, and DT throughout projects' lifecycles. The model also considers the regulatory aspect and the environmental aspect, and the circular economy (CE). The theoretical framework provides key technological building blocks for industry practitioners to develop the DDTC concept further and implement it through experimental works. Finally, the paper provides an industry-specific analysis and technological approach facilitating BCT adoption through DT to address the key challenges and improve sustainability for the BECOM industry 4.0.

Keywords: blockchain; PESTELS; construction; built environment; mining; BIM; IoT; digital twin; industry 4.0



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1. Introduction

1.1. General Information

1.1.1. The BECOM Industry

The BECOM Industry, as one of the largest industries in the world, faces key challenges such as decreasing productivity over the last decades compared to other manufacturing industries [1]. The BECOM industry is fragmented [2] as organizations work in silos in an adversarial manner [3], and the contractors act as central parties [4]. There are inefficiencies in the construction supply chain and rework due to miscommunication and inaccurate or inaccessible information, and this cost around \$31 billion in the US construction industry in 2018 [5]. Lack of trust is a major challenge [6] for the BECOM industry; poor regulations and compliance are also key issues in the industry [7]. The BECOM industry is slow to adopt new technologies [7] compared to other manufacturing industries. The industry's slower digitization [1] is due to short-term thinking, uncertainty, fragmentation of the

supply chain, lack of R&D investments, and a rigid culture regarding organizational and process changes [2]. The short duration and unique complexity of construction projects [2] lead to short-term thinking and hesitation to change. Short-term thinking is, however, less critical in the mining industry, where projects can last for decades.

1.1.2. Industry 4.0 Technologies

The fourth industrial revolution governed by digital technologies and the digitization of processes is referred to as industry 4.0. The key technologies of the BECOM industry 4.0 are BIM, cloud computing, mobile computing, mixed reality (MR), cyber-physical systems (CPS), robotics, IoT, and Big Data [1]. IoT can save from \$160 billion to \$930 billion each year on construction sites and mines [8]. However, the management of IoT networks is centralized [9] and hence prone to a single point of failure. BIM Level 1 and Level 2 are also centralized and prone to generate data silos [10], while BIM Level 3 is more collaborative but still relies on centralized clouds.

BCT is decentralized and secure by nature, and it has the potential to decentralize IoT networks governance and BIM management and improve security, traceability, and data integrity. BCT emerged in 2008 with the creation of the Bitcoin protocol [11] that uses open-source code. BCT has already shown its capacity to offer a decentralized, secure, transparent, open, auditable, and immutable shared ledger of transactions for the financial and supply chain industries. BCT should generate more than USD \$175 billion by 2025 and over USD \$3 trillion by 2030 [12].

The disruptive potential of BCT in the built environment was imagined with the “Blockchain of Circular BIM things” [13]. The large benefits of blockchain and its impact on construction businesses can justify its adoption. Since BCT has a significant role in connecting different technologies, devices, and stakeholders through peer-to-peer networks, its adoption will affect the connectivity [14] as a core promise for the BECOM industry 4.0. Leveraging BCT for the BECOM supply chain can decrease fragmentation; increase collaboration; improve efficiency; and enhance trust and transparency for processes, information sharing, and information management [15]. BCT is promising for the BECOM industry 4.0 and could contribute to saving costs and time, improving quality, enhancing safety, facilitating on-time and on-budget delivery, and improving communication and customer relationships while strengthening the industry’s image [7]. The Australian building confidence report considers that BCT could provide a verifiable shared digital audit trail of regulatory transactions [16].

The integration of BCT for DT, in particular, has great potential for the BECOM industry. DT represents the digital replica of a smart physical asset like a smart building equipped with IoT sensors. DT can generate considerable value throughout projects’ lifecycle for processes approval, automated monitoring, as-designed and as-built info, resources planning, logistics, safety monitoring, predictive maintenance, quality assurance, and compliance [17]. DT captures data from the information value chain of projects to improve the performance of assets and assist customers, owners, operators, governments, investors, and society in general [18]. The global market for DT was about USD \$3.2 billion in 2018 and has a projected value of \$29.1 billion by 2025 [17]. Greater data sharing could bring £7 billion per year across the UK infrastructure sectors [19].

The Gemini Principles provide an information management framework for the development of DTs in the built environment [19]. *The Gemini Principles* specify that the information value chain should be managed to decrease the data volume while the data value is increased [19]. Moreover, the trustworthiness of the data, its security, openness, and quality are key pillars of *The Gemini Principles* and concurrently the key features of BCT. Hence, BCT could be a suitable technology for DT to satisfy *The Gemini Principles*. DT ecosystems for the public good should be secure, reliable, trusted, open, transparent, collaborative, with data interoperability (format agnostic) and access control rules guaranteeing privacy [17]. BCT could guarantee the trust, security, and transparency required for integrated shared DT platforms [20] in accordance with *The Gemini Principles*.

BCT can enhance proof of provenance, data trustworthiness, data security, and data traceability for DT of manufacturing supply chains [21]. However, the literature available about BCT for DT is scarce, and some technical gaps need to be addressed, such as the evaluation of technical and non-functional requirements for BCT integration with DT applications, the integration of BCT with BIM and IoT, and the authentication of data to guarantee data integrity. The literature proposes that if distributed ledger technologies such as BCT are developed further and become fully mature, they can become reliable solutions to key challenges such as low productivity and poor financial processes [7].

1.2. Research Questions

Since BCT has a strong potential to improve the BECOM industry 4.0, it is important to efficiently facilitate its adoption. Hence it is key to identify what are the barriers affecting BCT adoption in the industry. Secondly, as BCT is a key technology to strengthen data integrity and the trustworthiness of DT, it is essential to evaluate what are the key technological factors affecting the adoption of BCT through DT in the BECOM industry 4.0. Thirdly, as these technologies are emerging and the literature is limited, it is crucial to identify the gaps around the adoption of BCT for DT. Hence the three research questions of this study are as follows:

1. What are the key challenges affecting BCT adoption in the BECOM industry?
2. What are the key technological factors affecting BCT adoption with DT in the industry?
3. What are the technological gaps around the adoption of BCT for DT in the industry?

1.3. Aim and Scope

The aim of this paper is to develop a technological framework, based on a novel conceptual model, for the integration of BCT with DT for projects of the BECOM industry 4.0. The conceptual model aspires to address the key challenges of the BECOM industry, and the aimed technological framework will contribute to narrowing the technical gaps around the combination of these technologies. Hence, to answer the research questions, the objectives of the paper are as follows.

1. The first objective is to identify the challenges of the BECOM industry 4.0 that either affect or can be improved with BCT adoption.
2. The second objective is to evaluate the key technological factors affecting the adoption of BCT in the BECOM industry 4.0.
3. The third objective is to propose a conceptual model for the integration of BCT and DT for projects of the BECOM industry 4.0.

For this purpose, this study reviews the literature about BCT and DT in the context of the BECOM industry 4.0. The first contribution of this paper is in Section 3, which presents the literature review following a PESTELS approach [2] to identify the key challenges affecting BCT adoption in relation to each PESTELS theme. The second contribution is in Section 4, which identifies the key technological factors affecting the adoption of BCT in the BECOM industry 4.0. The paper's main contribution is presented in Section 5 with the novel technological framework based on a conceptual model called the decentralized digital twin cycle (DDTC). The fourth contribution of the study is the identification of technological gaps concerning the adoption of BCT for DTs in BECOM 4.0. Finally, the paper discusses in Section 6 the contributions of the offered DDTC technological framework. Section 6 also discusses how the DDTC model can address some of the key challenges identified beforehand and how it contributes to narrowing the literature gaps. Furthermore, Section 6 presents the study's implications for the industry, its practitioners, and future research work. The originality of the paper provides an industry-specific analysis of the adoption of BCT coupled with a technological approach that leads to the development of a technological framework that provides key building blocks for industry practitioners to develop further and implement.

2. Methods

At first, a traditional literature review method was used, and papers related to BCT, DT, and IoT were identified according to the research criteria presented in this section. BCT is a revolutionary technology allowing people to exchange value and data in a peer-to-peer way without trusting centralized institutions. Hence BCT will have a transformative effect on society as a whole and offer a paradigm shift on various dimensions of society, including key macro factors—such as the political, economic, social, technological, environmental, legal, and security (PESTELS) factors. Consequently, a PESTELS approach [2] was chosen to review the literature and extract key information from the selected papers into each of the PESTELS categories.

The general method for this paper is qualitative and pursued the following steps: database selection, search criteria, selection of relevant papers, the definition of the research directions, identification of key challenges, the identification of technological factors, and the extraction of technical gaps. Furthermore, additional relevant technical papers were selected in order to perform content analysis and extract state-of-the-art techniques to narrow the gaps identified.

The main databases were selected for their relevance to the engineering field: Compendex, Scopus, and Engineering Village.

The search criteria used were:

- Blockchain OR “distributed ledger” AND “construction” OR “construction industry” OR “built environment” OR “building industry” OR building OR “mine” OR “mining”;
- Blockchain OR “distributed ledger” AND “BIM”;
- Blockchain OR “distributed ledger” AND “digital twin*” OR “cyber physical system*”;
- Blockchain OR “distributed ledger” AND “smart building*” OR “intelligent building*” OR “smart home*” OR “Internet of Things” OR “IoT”.

Papers were selected according to the quality of the journal (Q1 and Q2 journals prevailed over lower-level journals), the relevance to the topic, and the filtering by date of publication. BCT is in its infancy and evolves at a very fast pace. Thus, papers prior to 2017 were not selected except if their relevance was essential for this review. References are mostly dated from 2017, 2018, 2019, and a few recent papers from 2020 are also cited. Papers were selected based on their keywords, abstracts, and conclusions in terms of relevance to the topic. The main relevant keywords identified were: blockchain, smart contracts, distributed ledger, construction (industry), built environment, mining (industry), industry 4.0, smart building, intelligent building, smart home, BIM, digital twin, IoT, and cyber-physical systems. Most of the papers reviewed are key journal articles, with four conference papers also included. The papers were reviewed through a PESTELS approach, and the remaining references are related to specific technical papers selected for a content analysis of the blockchain technological state of the art for the purpose described in the preceding paragraph.

The PESTELS approach applied to review the literature permitted to extract key findings related to BCT adoption in the BECOM industry 4.0 for each PESTELS category. The information identified relates to industry-specific macro factors and to the key technologies: BIM, IoT, and DT. During the review of the papers, tables were produced to classify the extracted key information into every PESTELS category for each paper. It was then possible to identify and categorize the key challenges affecting BCT adoption in the BECOM industry 4.0 for each PESTELS category. From this categorization, the study then focused on the identified key technological (T) factors affecting the adoption of BCT and its relation to the key technologies: BIM, IoT, and DT.

Additional papers were further selected specifically for their relevance to the technological (T) factors identified; Hence the content analysis of the technological state of the art literature about BCT (whitepapers of key blockchain-based protocols) was performed to identify technical solutions aiming to address the key technological (T) challenges and factors identified in the literature. Subsequently, the paper proposes a technological frame-

work based on a conceptual model (DDTC) for the integration of BCT with DT. Additionally, from the technological factors affecting BCT adoption in the industry, it was then possible to extract the technological gaps relevant to the adoption of BCT for DT in particular. The study then articulates how some of the gaps identified are narrowed by the proposed DDTC framework.

3. Literature Review

The adoption of BCT in the BECOM industry 4.0 is promising to enhance trust, collaboration, efficiency, data sharing, and information security [7]. The existing literature offers key models such as “the blockchain of circular BIM Things” [13] and “the cup of water theory” [9], which both leverage BCT as a trusted container for information security for BIM and IoT. Naturally, this concept can be extrapolated from BIM and IoT to CPS [22], such as DT for which BCT could act as a core security component and as the layer of trust. However, several challenges affecting the adoption of BCT in the BECOM industry 4.0 should be considered first.

A PESTELS approach is used to review the literature and categorize the key challenges affecting BCT adoption for the BECOM industry 4.0. These key challenges identified in the literature are presented in the below paragraph and are more detailed in Table 1.

The political factors relate to the regulations of the BECOM industry and its limiting effects on the adoption of BCT due to a lack of regulations and policies for this new technology. Currently, the regulations on BCT are uncertain [2], and policy makers should admit the need for a new contractual and enforcement model leveraging BCT [4]. Hence, the BECOM industry needs regulatory changes to embrace digitization further [7]. The current regulatory framework originates from a centralized paper-based model that is disjointed from the blockchain paradigm shift that embraces the decentralization of services, and the automation of processes with smart contracts. A technological shift of the regulatory processes themselves would facilitate the adoption of BCT in the BECOM industry 4.0.

The economic factors refer to economic performances, efficiency, productivity, and costs in relation to the adoption of BCT. The productivity in the industry is stagnating [9], and efficiencies are generally low [22]. The financial ecosystem of the industry is generally fragile, and the pricing model is adversarial [7]. Moreover, financial transparency is lacking in the BECOM industry [2]. However, the high implementation cost of BCT is a key challenge for adoption as margins are low in the BECOM industry [7]. BCT may be costly to implement, however once adoption is generalized, the longer-term financial benefits for the BECOM industry 4.0 are likely to be significant and make the former centralized model obsolete due to overhead costs and inefficiencies.

The social factors refer to cultural aspects, workforce demographics, lack of skills, trust, industry habits, and attitudes that affect BCT adoption. The key social challenges for the BECOM industry are a poor industry image, its structural fragmentation, the lack of collaboration, lack of trust [23], and lack of transparency [22]. Indeed, the BECOM industry is fragmented [15] in data silos that restrict collaboration, limit trust in data governance [24], and create inefficiencies in information sharing and information management. The lack of trust in the industry leads to adversarial behaviors incentivizing stakeholders to hold information instead of sharing data for the benefit of the projects. BCT is decentralized, open, and secure by nature; moreover, it leverages cryptocurrencies as an incentivization mechanism to ensure that participants ‘play by the rules’ of the blockchain protocols consensus. Consequently, blockchain based systems could incentivize stakeholders of BECOM projects to share data in order to enhance collaboration in a competitive environment. Therefore, BCT is likely to optimize cooperation in the BECOM industry 4.0.

The technological factors refer to technological aspects, limitations, and requirements affecting the adoption of BCT for the BECOM industry 4.0. Some fundamental technological challenges for BCT adoption are the requirements for specific advanced IT infrastructures [22] and the need for efficient blockchain consensus mechanisms ensuring energy efficiency [23]. Moreover, the blockchain trilemma limits the capacity of a blockchain

network to achieve at the same time decentralization, scalability, and security [25]. Other key challenges limiting BCT adoption relate to technical requirements of the BECOM industry 4.0, such as the interoperability between different blockchains [7], transaction privacy, network governance, and the integration of BCT with other key technologies of the industry such as IoT, BIM, and DT. Currently, DT solutions are too centralized, which induces single point of failure vulnerabilities. Additionally, data sharing for DT needs to be secured throughout the lifecycles of the physical asset that is represented by the DT [26]. There are key technological factors affecting BCT adoption for DT in the BECOM industry 4.0. Indeed, DT applications are typically centralized, leverage Big Data analysis and storage, and enable privacy as required with siloed databases and strict access control mechanisms. Whereas BCT is decentralized, has very limited storage capacity, and its openness by nature makes confidentiality a major challenge. Hence, critical trade-offs and state-of-the-art techniques need to be explored and discussed to integrate BCT with DT in order to improve DTs security with blockchain.

The environmental factors refer to environmental sustainability, energy consumption, and recycling and reuse of materials. Materials wastes are a challenge for the BECOM industry [27]. The main environmental challenge for blockchain adoption is the energy consumption [7] of the consensus mechanism of certain public blockchain networks using proof-of-work (PoW) 'mining' which consumes large amounts of electricity. BCT can enhance waste management through traceability of materials along the lifecycle of projects. However, the carbon savings accomplished with materials recycling and reuse, should not be counterbalanced by the carbon emissions due to the energy consumption of blockchain based protocols. Hence, the energy efficiency of blockchain protocols is a critical factor to achieve substantial benefits for the environment in the BECOM industry 4.0.

The legal factors refer to contractual and legal aspects affecting the adoption of BCT in the BECOM industry. The key legal challenges in the BECOM industry relate to legal disputes, breaches of contracts, poor payment practices, and compliance issues [6]. The standards and regulations are stringent in the BECOM industry, but the certifications practices are substandard [21]. There is also a lack of standardization for BCT [26], and there are compliance challenges between BCT and the General Data Protection Regulation (GDPR) developed in Europe [28]. Moreover, proving ownership and liabilities is challenging [15], notably for the ownership of BIM models [4]. BCT and legal smart contracts can enforce accountability and non-repudiation through traceability of legal information, digital identities, and data ownership.

The security factors refer to the cyber security aspects that are affecting the adoption of BCT in the BECOM industry. With the digitization of the industry, cyber threats represent a primary risk for organizations [2]. Data privacy [22], data security, and data protection are major challenges of the industrial revolution 4.0 [1]. BCT is decentralized and secure by nature, hence BCT offers a paradigm shift from the existing security model of centralized infrastructure that are currently isolated in data silos secured by firewalls. Whereas BCT can guarantee security with trusted open networks that are secured by cryptography and public key infrastructure. This cyber security paradigm shift offered by BCT has considerable potential to decentralize and secure IoT networks [23] and DT data sharing [26] against malicious attacks.

Table 1 summarizes the PESTELS challenges affecting BCT adoption in the BECOM industry, that were identified through the literature review.

Table 1. Summary of the challenges related to BCT adoption in the BECOM industry 4.0.

PESTELS Challenges		References
Political challenges		5 references
Uncertain regulations	P1	[2]
Inadequate regulatory oversight and enforcement tools	P2	[7]
Poor regulation and compliance	P3	[1,7]
Need for regulatory changes to adopt digitization	P4	[7]
Regulatory difficulties between BCT and GDPR	P5	[23]
Policymakers and lawyers need to recognize the demand for a new contractual model and to deliver it efficiently	P6	[4]
Economic challenges		7 references
High implementation cost	E1	[1,7,22]
Lack of financial transparency	E2	[2]
Low efficiency	E3	[6,9,22]
Supply chain inefficiencies	E4	[6]
Stagnating/Low productivity of the construction industry	E5	[4,7,9]
Low predictability	E6	[7]
Low margins	E7	[7]
Increasing costs	E8	[6]
Adversarial pricing models and financial fragility	E9	[7]
Lack of R&D and investments towards innovation	E10	[7]
Exchange rate volatility of cryptocurrencies	E11	[7]
Quality issues	E12	[6]
Delays	E13	[6]
Lose collaboration and inefficient management techniques	E14	[9]
Inefficient communication	E15	[6]
Limitations of the traditional funding and delivery model	E16	[7]
Poor supply chain management	E17	[6]
Social challenges		12 references
Acceptance of new technologies	S1	[1]
Hesitation to adopt new technologies	S2	[1,29]
Lack of knowledge and skills regarding BCT and new technologies	S3	[1,6,22]
Cultural habits in the construction industry	S4	[2]
Lack of trust	S5	[6,9,21,23]
Lack of transparency	S6	[22]
Workforce size and demographics	S7	[7]
Lack of collaboration and lack of improvement culture	S8	[7]
Poor industry image	S9	[7]
Structural fragmentation of the industry	S10	[6,7,15]
Resistance to organizational and processes changes	S11	[1,2,7]
Lack of collaboration and trust in data governance	S12	[24]
Contractors acting as a central third parties	S13	[4]
Adversarial industry	S14	[6]
Dysfunctional training	S15	[7]
Slow adoption of new technologies by the construction industry	S16	[7]
Readiness for adoption of new technologies	S17	[7]
Technological challenges		14 references
IT infrastructure requirements		5 references
Higher requirements of BCT for computing equipment	T1	[1]
Need to enhance existing communication networks	T2	[1]
Blockchain requires specific IT infrastructure	T3	[22,23]
Storage capacity requirements for BCT	T4	[22]
Bandwidth and connectivity requirements for BCT	T5	[7]
Lack of standards and reference architectures	T6	[1]
Governance of networks	T7	[2]
Digital twin (DT) challenges		4 references
Complex data specifications for DT (descriptive and sensor data)	T8	[26]
Need for DT throughout complex asset lifecycle	T9	[21]
Requirement to secure the data sharing of DT	T10	[26]
Current DT solutions are too centralized and rely on PLM system	T11	[26]

Table 1. Cont.

PESTELS Challenges		References
Need for a DT federated model aggregating all the models	T12	[24]
Data storage requirements for the Big Data collected during DT lifecycles	T13	[24]
DT for multi-party sharing need to support data variety, data velocity, data integrity, confidentiality, read and write operations	T14	[26]
DT and IoT need high throughput and tamper resistant systems (authenticity, provenance, proof of ownership, lifecycle traceability, data input from IoT)	T15	[24]
Need for IoT enabled devices for each building system	T16	[7]
Data requirements for DT		9 references
Data security	T17	[1]
Data format variety	T18	[26]
Data velocity	T19	[26]
Data volume	T20	[15,24]
Data ownership	T21	[15,24,26]
Data integrity	T22	[6,22,23]
Authentication and trustworthiness of the data	T23	[7,22]
Data availability	T24	[23]
Data privacy	T25	[23]
Data interoperability for information sharing	T26	[6]
Data management as per <i>The Gemini Principles</i>	T27	[19]
Traceability and transparency (non-functional requirements)		6 references
Need for traceability and transparency of information	T27	[21]
Necessity to track components	T28	[6,21]
Need for immutable audit trails to track and trace	T29	[24]
Lack of transparency and traceability in the construction supply chain because of high number of participants and short timeframes	T30	[9]
Need for traceability, transparency	T31	[6,21,22]
Lack of real time information	T32	[6]
Lack of data traceability in the industry	T33	[15]
Identity management		2 references
Need for decentralized identity management for humans or IoT	T34	[24]
Technical challenges for IoT: access control and authentication	T35	[23]
Decentralization (non-functional requirement)		3 references
Industrial networks are too centralized	T36	[22,23]
Unnecessary trusted third parties in the industry	T37	[22]
IoT management is limited because of centralized databases systems vulnerable against attacks	T38	[9]
Blockchain performances challenges		6 references
BCT has a low throughput compared to centralized databases	T39	[6,7,23]
Lack of scalability of BCT	T40	[15,23]
High latency of BCT	T41	[6,7]
Blockchain interoperability	T42	[7,22]
Proof-of-work (PoW) i.e., mining is not energy efficient	T43	[23]
Difficulty to develop new blockchain consensus mechanisms	T44	[22]
Blockchain network access challenges (permissioned or permission-less)	T45	[22]
Choice between public or private blockchain	T46	[22]
Security and tamper proof requirements for the industry	T47	[22,23]
Blockchain scalability trilemma: trade-off between scalability, decentralization, and security	T48	[25]
Privacy requirements for the industry	T49	[22,23]
Resilience against cyber-attacks is required in the industry	T50	[22]
Data storage limitations on the blockchain	T51	[15,23]
Asset's lifecycle complexity		4 references
Complexity of assets life cycles (design, build, inspect, monitor, certify and manage) for DT	T52	[21]
Broken information flow across lifecycle phases is a challenge for DT that can be addressed by BCT	T53	[26]

Table 1. Cont.

PESTELS Challenges		References
Traditional life cycle management (LCM) issues such as data sharing and efficiency apply to building LCM through BIM	T54	[9]
Difficulty to reuse existing blockchain network due to the one-off nature of construction project	T55	[6]
BIM challenges		4 references
Difficulty to track changes in BIM models	T56	[15,30]
Attacks from the BIM central operator cannot be recorded and tracked	T57	[30]
Blockchain cannot scale in terms of storage for BIM data, it can only record the digital proof	T58	[15,30]
BIM model information is currently stored in data silos containing different models' versions	T59	[9,15]
Difficulties to guarantee the integrity of historical BIM data	T60	[30]
Lack of storage and scalability of BCT to run BIM model entirely on BCT as a decentralized application	T61	[7]
Difficulty to achieve confidentiality with BCT	T62	[15]
Need for disintermediation in the industry	T63	[15]
Need for inter-organizational recordkeeping	T64	[30]
Smart contracts challenges		1 reference
Difficulty to code smart contracts	T65	[7]
Challenge to program bug free smart contracts which are permanently stored on the blockchain	T66	[7]
Digitization challenges		3 references
Slow development of the AEC/FM (facility management) industry due to slow/poor digitization	T67	[7,9]
Usage of different digital tools: interoperability issues	T68	[26]
Lack of adequate collaboration and information sharing	T69	[7]
Lack of a single source of truth in the AEC/FM industry	T70	[9]
Other challenges		4 references
Technical challenges	T71	[2]
Increased structural demand on buildings (similar to airplanes in the aircraft industry)	T72	[21]
Need for systems flexibility	T73	[22]
Off chain storage paired with distributed hash tables (DHT) for each blockchain node	T74	[26]
Environmental challenges		3 references
Energy consumption of BCT	EN1	[7,22,23]
Materials waste in the industry	EN2	[27]
Legal challenges		11 references
Standards and Compliance		4 references
Lack of standards for blockchain	L1	[26]
Stringent standards, regulations, and certifications in the industry	L2	[21]
Legal disputes and compliance issues	L3	[6,22]
Contractual		6 references
Legal and contractual uncertainty	L4	[1]
Traditional contracts are time consuming and involve several parties	L5	[9]
Contracts breaches are frequent in the industry	L6	[6]
Poor payment practices (late payments, not paid, held up payments) and associated contractual issues	L7	[7]
Non-repudiation	L8	[15,23]
Ownership and liabilities		4 references
Difficulty to prove intellectual property rights (ownership, immutability)	L9	[15,24]
BIM model ownership is an issue for legal disputes	L10	[4,15]
Lack of clarity on roles and responsibilities	L11	[7,15]
Lack of enforceability is a key challenge as it is very difficult to know who to hold accountable	L12	[7]

Table 1. Cont.

PESTELS Challenges		References
Security challenges		8 references
Data security and data protection	SE1	[1]
Management and security of information shared within the supply chain	SE2	[24]
Current security methods need to build barriers/firewalls around IT infrastructures	SE3	[30]
Need for a dynamic and adaptable security framework	SE4	[23]
Blockchain based IoT security and privacy	SE5	[23]
Need for data privacy	SE6	[9,22]
Centralized third parties are vulnerable as single points of failure	SE7	[9]
Need for privacy aware distributed hash table (DHT)	SE8	[31]
Resilience against combined attacks is a challenge for BCT and IoT	SE9	[23]
Cyber security risks	SE10	[2]
Malicious attacks/hacking of IoT	SE11	[7,23]

P1, ..., E1, ..., S1, ..., T1, ..., EN1, ..., L1, ..., SE1, ... refer to the ID of respectively each political, economic, social, technological, environmental, legal, and security factors.

The PESTELS categorization (summarized in Table 1) of the key challenges in the industry affecting BCT adoption satisfies the first objective of the paper. It should be noted that the technological (T) challenges affecting BCT adoption are subdivided in Table 1. as follows: IT infrastructure, BIM, digital twin (DT), data requirements for DT, traceability and transparency, decentralization, identity management, blockchain performances, smart contracts, asset's lifecycle complexity, and digitization of the industry.

4. Key Technological Factors Affecting Adoption

As mentioned in the method section, a content analysis of the state-of-the-art literature on BCT was also performed in parallel. From this technical content analysis, the key technological (T) factors affecting BCT adoption in the BECOM industry 4.0 (shown in Table 1) were reorganized logically in key categories consistent with the key technical challenges and taxonomy around BCT. The categories of key technological (T) factors affecting the adoption of BCT in the BECOM industry 4.0 are presented in Table 2, which frame the validation of the second objective of this paper. The key technological factors shown in Table 2 are the IT requirements for BCT, the technical requirements for BCT applications, and the integration of BCT with other technologies (BIM, IoT, and DT) of the BECOM industry 4.0. In order to fully satisfy the second objective of this paper, the technological factors are explained further in Section 4. The third column of Table 2 compares the technological factors with key related use cases and technological components obtained from both the literature review and the content analysis of the state-of-the-art literature on BCT. This identification of key technological factors sets the foundations and provides the building blocks for the technological framework proposed in Section 5.

Table 2. Key technological factors affecting the adoption of blockchain technology in the BECOM industry.

Group		Key Technological Factors	Uses Cases and Technological Components References
A. IT requirements	1	Decentralization	<p>Open-source code for BCT protocols [11,32].</p> <p>Decentralized payments and smart contracts to automate processes [4].</p> <p>Decentralized applications (DApp) and decentralized autonomous organizations (DAO) which could be integrated with BIM [9].</p> <p>BCT removes intermediaries [7].</p> <p>BCT eliminates the need for security barriers which generate data silos [30].</p>
	2	IT infrastructure and computational requirements	<p>Distributed computing solutions such as iExec [33] or Dfinity [34] could compute decentralized applications of the BECOM industry.</p> <p>Off chain decentralized data storage could be mapped to blockchain through distributed hash tables (DHT) [26].</p> <p>Decentralized storage [23] such as Storj [35] and distributed storage, such as Swarm [36] or IPFS [37], could be suitable when they become adequately scalable for applications of the BECOM industry like BIM.</p> <p>BCT would need to be adequate for data variety, data velocity [26], and data volume [15].</p>
	3	Big Data requirements	<p>To guarantee data integrity from IoT devices, data should be authenticated using crypto hardware secure element [38] before entering the blockchain to avoid “garbage in, garbage out” (GIGO) effects.</p> <p>Data interoperability is required for the information sharing industry [6].</p> <p>Data security and privacy are key requirements for the BECOM industry 4.0 [9,22,23].</p> <p>Real-world project data could be input to the blockchain through decentralized oracles like Chainlink [39].</p>
B. Blockchain applications requirements	4	Smart contracts integration	<p>Disintermediate and automate processes [22].</p> <p>Release payments automatically when tasks are completed [4].</p> <p>Manage project bank accounts [7].</p> <p>Save time, increase efficiency, reduce manual errors, record BIM operations and allocate ownership and responsibilities, secure transactions of properties, land ownership, equipment leasing/purchase, and procurement, facilitate IoT management challenges [9].</p> <p>Enable DApps [23] and DAOs [9].</p> <p>The Ethereum platform [32] integrates smart contracts, has a major public blockchain, and its protocol can also be leveraged for consortium and private blockchain networks.</p>
	5	Identity management/access control	<p>The uPort project [40] offers a blockchain-based decentralized identity service for the citizens of Zug in Switzerland.</p> <p>The ERC-725 project is a blockchain-based self-sovereign identity standard on Ethereum [41].</p> <p>To enhance privacy, zero-knowledge proof can be used for community self-sovereign identity [42], for IoT devices identities [43], and to manage access control for DHT [31].</p> <p>Identity authentication for IoT devices can be achieved with crypto hardware such as the secure element by Riddle and Code [38].</p>

Table 2. Cont.

Group	Key Technological Factors	Uses Cases and Technological Components References	
6	Blockchain properties and performances	<p>The scalability trilemma [25] claims that there is a trade-off between the three key requirements of a blockchain network: scalability, decentralization, and security.</p> <p>Private, consortium, and public [30].</p> <p>Proof of Authority (PoA) consensus mechanism [44] for private and consortium blockchains.</p> <p>Governance of private nodes with Infrachain [40].</p> <p>Anchorage of dataset's hash proof to overcome scalability challenges [40].</p> <p>Proof of Stake (PoS) consensus mechanisms for public blockchains like Ethereum 2.0 [45] with Casper [46] or Cardano [47] with Ouroboros [48] which are more energy efficient than proof-of-work (PoW).</p> <p>Blockchain privacy projects: Aztec [49], Enigma [50], and the Baseline protocol [51].</p> <p>Blockchain interoperability projects: Cosmos [52], Interledger [53], Polkadot [54], Quant [55], or APIs and Oracles [56].</p>	
C. Blockchain integration with other technologies	7	Blockchain integration with BIM	<p>Blockchain can provide immutable records for the sharing of historical BIM data [30] in a trusted collaborative environment [9].</p> <p>Real-time model updates from network participants based on their access rights [7].</p> <p>Signing of BIM models with the BIMCHAIN software [57].</p> <p>BIM Level 3 and BCT can bring a single shared source of truth of the BIM model in a distributed, trusted collaborative environment [9].</p> <p>BIM Level 3 complies with Industry Foundation Classes (IFC) and BuildingSMART Data Dictionary (bsDD), which could be integrated to BCT [7] through a standardized data structure, with hash proof of BIM data, recorded into the blockchain blocks [30].</p> <p>New BIM dimensions could be considered [58] in relation to BCT such as a financial dimension enabled by decentralized blockchain payments or a contractual dimension through smart contracts.</p> <p>To overcome data storage limitations on the blockchain, distributed hash tables (DHT) could be used [23] to map the blockchain hash proofs to cloud storage.</p> <p>Decentralized [35] and distributed storage [36] will likely become adequately scalable for a large volume of BIM data.</p>
8	Blockchain integration with IoT	<p>BCT can defragment IoT ecosystems through decentralization of the IoT networks' management [9].</p> <p>Network of validators nodes for IoT devices should be sufficiently distributed as per the INCUBED protocol [59].</p> <p>IoT data collected through the value chain can update the ledger, providing a single source of truth to track components, avoid duplication of work and improve facility management [7].</p> <p>Blockchain can act as a secure and transparent container for historical IoT data [9].</p> <p>Ethereum, Hyperledger Fabric, and IOTA are suitable DLT for IoT [60].</p> <p>Ethereum blockchain is public and has a native cryptocurrency Ether (ETH), whereas Hyperledger is not public and does not have a native currency. Ethereum enables smart contracts while IOTA do not.</p> <p>However, Ethereum requires a transaction fee on its public network, whereas IOTA does not.</p> <p>Crypto hardware secure elements [38] embedded into IoT devices can authenticate IoT devices and IoT data to enhance data integrity.</p> <p>Resource-constrained IoT devices can offload computation to master validating nodes [60] using fog computing at the edge of the network [61].</p> <p>Energy harvesting for IoT devices is integrated to mining equipment so that IoT devices batteries can be recharged using the vehicle's vibrations [62].</p>	

Table 2. Cont.

Group	Key Technological Factors	Uses Cases and Technological Components References
9	Blockchain integration with digital twin	<p>DLT is suitable to secure DT data [26].</p> <p>Decentralized common data environment (DCDE) [9].</p> <p>Distributed collaborative environment can benefit the project information model (PIM) and the asset information model (AIM) [63] throughout the lifecycle of the asset and its DT.</p> <p>Big Data from the project information value chain should be managed in accordance with <i>The Gemini Principles</i> in order to reduce data volume and increase data value [19]</p> <p>IoT, BIM, and blockchain can also enhance real-time monitoring for construction processes and management of facilities [7].</p> <p>A blockchain-enabled CPS architecture—i.e., BCPS—could use three layers [22]: the cyber net in the back end, the connection net for the sensing network of IoT, and the data monitoring management net presenting data insights to end-users through front end applications.</p> <p>Analogy with the “cup of water” theory [9], DTs represent the foundation (“cup base”) of digitization for the BECOM industry 4.0, IoT collect authenticated real-world data flow (“water”) throughout the projects value chain, and blockchain acts as the “cup wall” containing the data securely and efficiently in a transparent way.</p>
10	Asset lifecycle complexity	<p>DLT can unify the fragmented information flow across phases of the projects’ lifecycle [26].</p> <p>BECOM industry projects data can be recorded on the blockchain throughout the various phases of their lifecycle: design, manufacturing, materials delivery/procurement, construction processes, inspection certification, QA, asset management, decommissioning, and demolition [21].</p> <p>Blockchain-based information management throughout the lifecycle of the asset’s digital twin can benefit the CE [26] and improve sustainability [64] as it facilitates traceability of materials for reuse and recycling.</p>

The key technological factors affecting BCT adoption shown in Table 2 are grouped into the three key categories A, B, and C that is discussed as follows.

Table 2 refers to the three main factors related to information technology (IT) requirements (Group A). The first IT requirement is to achieve adequate decentralization of networks in the industry since decentralization is at the essence of BCT that provides an immutable trusted distributed ledger (through peer-to-peer networks) without relying on centralized trusted third parties [9]. The second IT requirement relates to the decentralization of IT infrastructures and computational capacities using, for example, decentralized trusted off-chain computing [33] and decentralized storage systems [35]. Thus, decentralized applications (DApps) and data storage requirements for BECOM industry applications would not rely on centralized IT systems that are vulnerable to cyber threats. In terms of data storage, off-chain decentralized storage could be mapped to the blockchain using systems like distributed hash tables (DHT) [26]. The third IT requirement is the integration of BCT with the data value chain of the BECOM industry. Big Data transacting throughout BECOM projects’ lifecycles follows the 3Vs characteristics comprising the variety of data formats (CAD, BIM, GIS, IFC, XML, COBie, planning, design cost, IoT, RFID, survey, asset information), data velocity, and data volume. Moreover, data authentication, integrity, interoperability, security, and privacy are key non-functional requirements to address for the data value chain in the industry. Adequate data structures, schemas, and standardizations are required to integrate an authenticated, structured, and trusted data layer into the blockchain from the project value chain.

Table 2 refers to three key requirements for blockchain (Group B) applications in the BECOM industry 4.0. Blockchain smart contracts are programmable transactions that can automate key processes such as business logic, and are executed in a decentralized way. Hence, smart contracts have great potential to automate processes and remove middlemen [22] in the BECOM industry 4.0. The integration of smart contracts is a key requirement for blockchain applications BECOM industry 4.0 as presented in Table 2. Smart contracts can also contain hash values guaranteeing the integrity of sensors data stored off the chain [26]. The second requirement is a digital identity and access control framework that is required to authenticate projects' stakeholders and IoT devices transacting through blockchain applications. IoT devices identities can be protected with crypto hardware secure elements [38] to guarantee data authentication at the source. The third requirement for blockchain applications in the BECOM industry 4.0 relates to key non-functional requirements for blockchain networks which are: scalability, security, decentralization, interoperability, privacy, governance, and energy efficiency. As mentioned previously, the blockchain trilemma [25] means that the scalability, security, and decentralization of the network cannot be satisfied altogether without one being compromised. Hence trade-offs are required between these three fundamental properties when designing blockchain applications. Finally, in terms of blockchain governance, there are three types of blockchain networks to consider: private, consortium, and public [30]. Privacy is also a key technological (T) factor affecting the adoption of BCT applications in the BECOM industry. It is naturally easier to achieve privacy with private blockchains, whereas it is a key challenge for public blockchains to enable private transactions. Achieving complete privacy on public blockchain networks appears counter-intuitive; however, privacy protocols like Aztec [49] using zero-knowledge proofs, Enigma [50], the Baseline protocol [51], or encryption mechanisms could be leveraged. Finally, interoperability between blockchains is a key technological (T) factor affecting BCT adoption in the BECOM industry due to the possibility of many stakeholders using blockchain applications built on different blockchain networks but that still require transacting together. Figure 1 considers the interoperability requirement between the stakeholders' blockchain ledgers within the BECOM industry.

Table 2 shows that there are concerns in the literature about the integration of BCT with the other key technologies of the BECOM industry 4.0 like BIM, IoT, and DT (Group C). BIM historical data and model changes can be recorded immutably on blockchain distributed ledgers [30]. Hence, BCT can enhance trust and transparency, prove ownership, responsibilities, liabilities, and intellectual property rights for BIM [7]. In addition, smart buildings' IoT sensors should inform the model about maintenance requirements in real-time [4]. The historical data of smart building assets should be recorded on the blockchain. However, blockchain has very limited storage capacity, making it practically impossible to store BIM and IoT data. Anchoring hash proofs of BIM data into the blockchain blocks [30] is an alternative method to overcome blockchain storage limitations. BIM Level 3 complies with Industry Foundation Classes (IFC) and BuildingSMART Data Dictionary (bsDD), which needs to be integrated into BCT [7] through a standardized data structure and data schemas. Other key challenges for the integration of BCT and IoT are the authentication of IoT devices and IoT data [22], the need to decentralize IoT networks' management [9], and resource-constrained IoT devices which have the limited computational capacity to operate full blockchain nodes [60]. Regarding DT, blockchain needs to provide a verified data audit trail and bring trust and transparency to DT ecosystems [20] throughout the project's complex lifecycle over a decentralized common data environment (DCDE) [9].

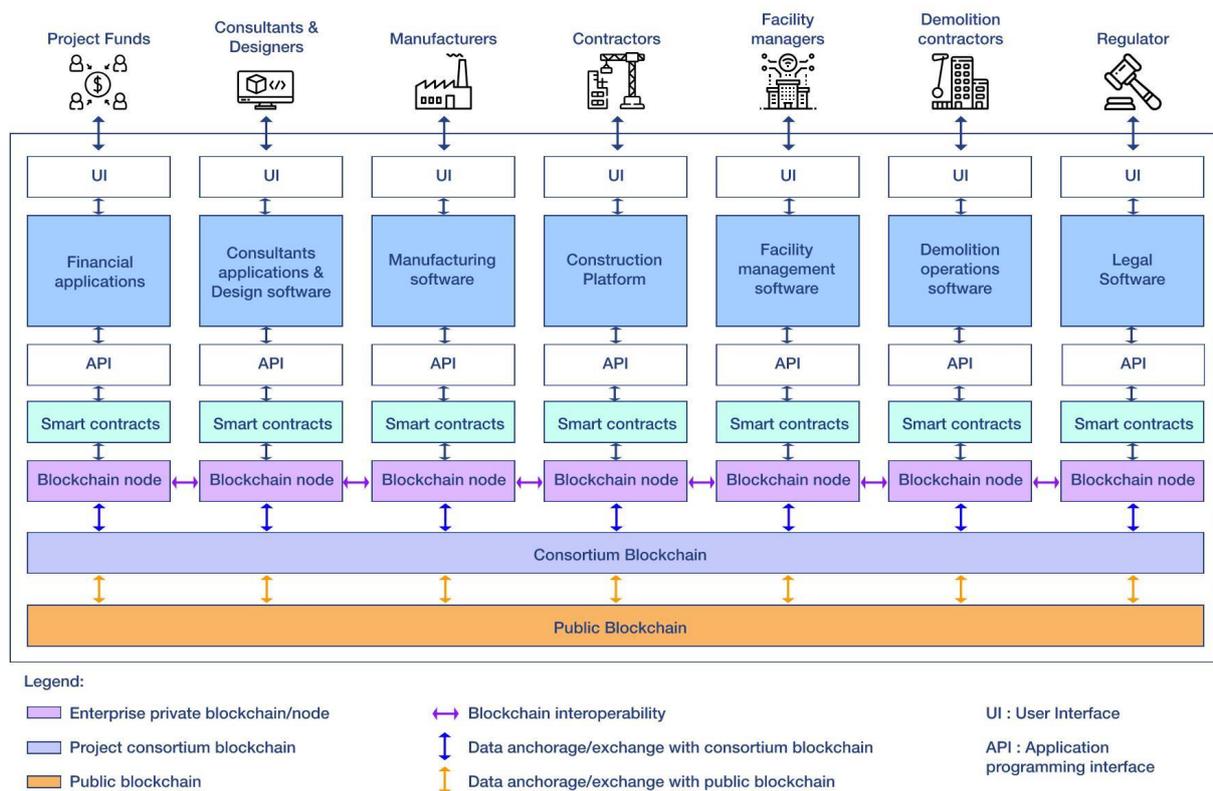


Figure 1. Blockchain ecosystem diagram between industry stakeholders at different levels: enterprise, consortium, and public. Adapted from Figure 10 of the World Economic Forum. Inclusive Deployment of Blockchain for Supply Chains: Part 6—A framework for Blockchain Interoperability; 2020 [56].

The technological (T) factors described above affect the integration of BCT with DT, which is a key technology of the BECOM industry 4.0 composed of IoT, BIM, data storage systems, computing layers, and Big Data flowing from the project information value chain. Since this study focus particularly on the combination of BCT and DT in the BECOM industry 4.0, the following section proposes a technological framework based on a novel conceptual model combining BCT and DT. The key technological factors presented in Table 2 and discussed in Section 4 provide the technological building blocks for the framework proposed in Section 5.

5. Decentralized Digital Twin Cycle

The paper offers the decentralized digital twin cycle (DDTC) conceptual model, comprising three core blockchain layers. BCT is at the core of the model, acting as the data integrity enabler that securely records key historical proofs for data transacting with DT throughout the lifecycle of projects in the BECOM industry 4.0. The DDTC has four key architectural layers: the connection layer, the data management layer, the computing layer, and the blockchain layer. Data from the BECOM project enters the DDTC through the external connection layer, which leverages software APIs (application programming interface), middleware, IoT devices, and RFID to capture “real world” project data across the various phases the project lifecycle. The information from the project data value chain enters the DDTC, and the data management layer comprises the information management framework in conformity with *The Gemini Principles* [19]. The data management layer also contains the DT applications user interfaces (front-end UI) for project participants to interact with the DT systems according to their access rights. The computation of the DDTC occurs within the computing layer. Ultimately, the blockchain core layer contains the project historical proofs of key data transacted with DT applications through immutable blockchain ledgers guaranteeing data integrity.

The DDTC model was developed by considering the nine key technological factors (A.1, A.2, A.3, B.4, B.5, B.6, C.7, C.8, C.9) presented in Table 2 in Section 4. The following chapters explain how each of the technological factors is considered by the DDTC framework.

In terms of IT requirements, the computing layer of the DDTC framework embraces decentralization in order to remove intermediaries and reduce data silos (key factor A.1). For this purpose, it leverages distributed blockchain ledgers and decentralized applications (DApps, DAOs) programmed with an open source ‘culture’ for smart contracts code. The IT infrastructure of the DDTC also aims to be decentralized (key factor A.2) by leveraging distributed trusted computing protocols [33] and distributed storage systems [35], both running off the blockchain. Despite being ‘off chain’, these distributed computing and storage protocols still leverage BCT for security and access control to guarantee cyber resilience. The DDTC technological framework also needs to interoperate with Big Data from the information value chain of BECOM projects (key factor A.3). Middleware solutions contribute to standardizing the data structure before it can enter the back-end components. The framework also leverages decentralized oracles [39] protocols to authenticate external data (from IoT sensors, external APIs, or from various web sources) before inputting them into the blockchain layer. Once the correct data enters the blockchain, they become secure, and data integrity is maintained over time. Finally, the model considers the data privacy requirement through the use of private blockchains, privacy protocols [49,51], and encryption mechanisms.

In terms of BCT requirements, the integration of smart contracts (key factor B.4) is a key component of the DDTC computing layer to automate processes, increase efficiency, trace accountability, and enable DApps. Smart contracts would be programmed to compute key processes along the project lifecycle. The DDTC model also leverage decentralized digital identities (key factor B.5) such as self-sovereign identities [42] for project stakeholders and devices identities. Decentralized identities would improve access control mechanisms for DApps of the DDTC framework. In terms of blockchain properties and performances (key factor B.6), the DDTC suggests combining private blockchains, consortium blockchains, and public blockchains. Private blockchains would be suitable at the enterprise level, consortium blockchains would be adequate for an overall project ecosystem (e.g., for joint ventures), and public blockchains would be suitable for the data required to be openly available for the public auditability. At the enterprise level, employees could transact certain key information (e.g., BIM historical data, design parameters, IoT data, contracts, financial transactions, workflows, and approvals) through the enterprise private blockchain network. This enterprise-wide shared ledger would represent a single source and reduce data silos internally. The transaction throughput of a private blockchain is highly scalable, and there is no transaction fee. At the project level, cooperating organizations would transact data together via a consortium blockchain adequately interoperable with the enterprises’ private networks, shown in Figure 1. The transaction throughput of consortium blockchains would be fast or moderate, depending on the type of data and the settlement finality requirements. When large volumes of data need to be transacted efficiently, settlements by packet could ensure that only key states hashes (digital footprints) are anchored in the shared ledger without transacting the actual datasets that can be stored off the blockchain. The transaction cost of such a consortium blockchain would be negligible and minimize the overhead costs of the project. The governance framework for private or consortium nodes could be achieved with systems like Infrachain [40]. At the public level, the projects stakeholders, and public external stakeholders (e.g., consumers and users) could transact and audit key data through a public blockchain that is open by nature. As such, public blockchains could serve as public registries that record transactions proofs [40] about key auditable data such as certificates, land registers, and environmental records. The transaction confirmation time and transaction cost for such a public blockchain would require relatively low for a viable user experience. Figure 1 illustrates this proposed mixed blockchain ecosystem combining private, consortium, and public blockchain for projects of the BECOM industry.

The transactions that require high throughput and privacy at the enterprise or project level can be processed respectively on the private and consortium networks. Only data requiring public audibility can be anchored on the public blockchains. Hence, the DDTC aims to address the blockchain trilemma with the combination of interoperable private, consortium, and public blockchains. Consequently, the scalability requirements of the project can be addressed by the proposed model.

In terms of BCT integration with other key technologies of the BECOM industry 4.0, the DDTC model connects BCT to BIM, IoT, and DT. The DDTC model aims to record in the blockchain the key historical data proofs from these technologies at each phase of the project to provide a single source of truth. BCT can be integrated with BIM (key factor C.7) in order to anchor key BIM data on the blockchain (on chain). For example, at the design phase, 3D BIM spatial data, real-time models' updates, and design parameters could be anchored on the blockchain ('on-chain'). 4D BIM scheduling, procurement, and supply chain data could be anchored on the chain during construction. During operation and maintenance, 6D BIM data, smart building IoT sensors data, and maintenance data could be anchored on-chain. As shown in Figure 2, the data management layer of the DDTC comprises the key processes that could be automated with blockchain smart contracts as well as the key data that could be anchored on-chain. Future research work should identify what project data exactly should be stored on-chain or off-chain. As mentioned in the previous chapters, the DDTC model contains decentralized storage systems to also preserve decentralization for the data stored off-chain. To integrate BCT with IoT (key factor C.8), the DDTC model aims to decentralize the connection layer with blockchain-based protocols for IoT management. For this purpose, the DDTC model promotes the use of edge computing systems (on-premises computing servers), enabling computation power near the IoT devices (at the edge) [61] to optimize the analysis of the data captured from IoT sensors. Moreover, having edge computing resources can allow resource constraint IoT devices to indirectly run blockchain nodes by delegating the computational effort to master nodes [60]. The connection layer of the DDTC model includes secure elements [38] and microchips [43] to authenticate devices identities and enable data authentication at the source to limit the GIGO effects. Hence, the initial data authentication and curation occurring at the edge enables the filtering of the data entering the DDTC to reduce volume and increase value according to *The Gemini Principles*, as shown in Figure 2 at the junction between the connections and the computing layer. Furthermore, the inclusion of blockchain-based protocols in the connection layer facilitates the decentralization of IoT management and reduces single points of failure. Finally, the DDTC model proposes to combine BCT with DT (key factor C.9) to improve information management throughout the complex lifecycle of a project by unifying fragmented data silos towards a single source of truth with key data securely anchored in the blockchain.

The DDTC model addresses the key technological factors (A.1, A.2, A.3, B.4, B.5, B.6, C.7, C.8, C.9) identified in Section 4. Moreover, the DDTC model facilitates collaboration through peer-to-peer distributed networks and benefits the CE through materials traceability, reuse, and recycling.

The diagram in Figure 2 represents the proposed technological framework based on the decentralized digital twin cycle conceptual model. The core blockchain layer comprises a combination of the private, consortium, and public blockchains, as described in the previous chapter and illustrated in Figure 1.

The following Section 6 discusses the contributions and implications of the DDTC framework as well as the associated gaps identified in the literature in relation to combining these technologies.

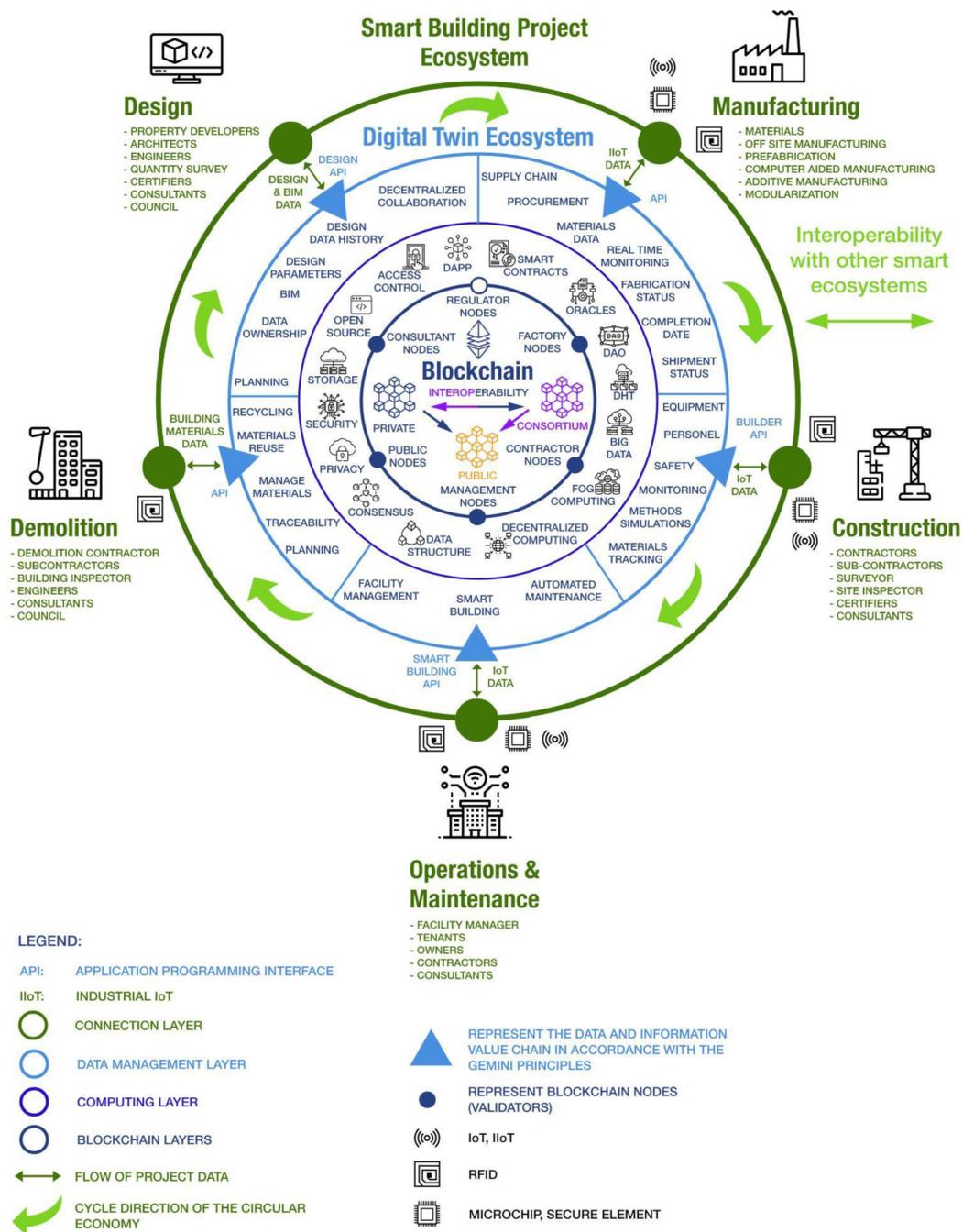


Figure 2. The decentralized digital twin cycle.

6. Discussion

The first contribution of the paper is a review of the literature following a PESTELS approach to identify the challenges affecting BCT adoption in the BECOM industry in all PESTELS categories. Hence, this approach is original since it identifies the key challenges related to the political (6 challenges), economical (17 challenges), social (17 challenges), technological (74 challenges), environmental (2 challenges), legal (12 challenges), and security (11 challenges) aspects as presented on Table 1. The paper then focuses on the technological factors which are predominant and form the main objectives of the study. The industry-specific technological challenges identified in the literature were then compared with the key technical blockchain solutions and protocols identified through the content analysis of the state-of-the-art literature on BCT. This allowed us to isolate the key technological factors affecting adoption and compare them with key use cases and technological

components in Table 2. This technological framework composed of key technological factors affecting adoption represents the second contribution of the paper. As presented in Table 2 of Section 4, nine key technological factors (A.1, A.2, A.3, B.4, B.5, B.6, C.7, C.8, C.9) were identified and categorized in three groups as follows: IT requirements (group A), blockchain applications requirements (group B), and the integration of blockchain with other technologies (group C).

Since BCT is not a mature technology yet, there are remaining technological limitations affecting its adoption for DT in the BECOM industry 4.0. Hence, from the key technological factors presented in Table 2, the study identified some key technology gaps areas in relation to BCT adoption for DT. These technological gaps should be addressed with future research work and the technological progress of BCT. Hence, the third contribution of the study is the identification of these technological gaps in relation to the adoption of BCT for DT in the BECOM industry 4.0. Indeed, the main focus of the paper was narrowed to five key technological gap areas contextualized to the adoption of BCT for DT in the BECOM industry 4.0. As shown on Table 3, the five gap areas identified in the literature are the technical and non-functional requirements of blockchain technology (gap area 1), technical limitations of IoT and blockchain technology association (gap area 2), BIM and blockchain challenges (gap area 3), digital twin data challenges with blockchain (gap area 4), and the complexity of projects lifecycles (gap area 4). These gaps areas cover a total of 14 themes for future research, as presented in Table 3. Finally, the main contribution of this paper is the development of a technological framework based on a conceptual model called the DDTC as presented in Section 5 and illustrated on Figure 2. Hence the theoretical contribution of the paper is linked to the proposed DDTC theoretical framework comprising the key technological components, and the sustainability and regulatory considerations that can be used by industry practitioners to develop the system and implement it. The DDTC model integrates technological components that contribute to narrowing some of the gaps identified. The content analysis of the technological state of the art on BCT permitted identifying potential solutions and protocols to address key technological factors and narrow the gaps as presented in the chapters below and summarized in the discussion column of Table 3. Finally, the contributions of the paper address the research questions raised in Section 1.

Table 3. Technical gaps analysis and themes for future investigations.

Area of the Gap	Themes for Future Research	PESTELS Factors	Discussion on the Themes
1. Technical and non-functional requirements of blockchain technology	1.1. Governance of the blockchain network [7,40]	P T L	Project stakeholders, including regulators, should run independent blockchain nodes. Validators' nodes can vote on key governance decisions. Infrachain project [40] offers a governance solution for private nodes. Explore decentralized governance models for blockchain networks.
	1.2. Type of blockchain network: private, consortium and public [7,22]	P Soc. T	The decentralized digital twin cycle model proposes to use private blockchains at the enterprises level, consortium blockchain at the project level and public blockchain to anchor key states for public auditability. The integration of these three types of blockchain networks for a project ecosystem is inexperienced, complex, and needs to overcome interoperability challenges [56].
	1.3. Scalability limitation of the blockchain network [23] to deal with the transactions data variety, velocity and volume [15,23]	T	The scalability of private, consortium, and public blockchains need to be all practically tested for the transactions' throughput of BECOM projects. Security and decentralization should be adequately maintained [25].

Table 3. Cont.

Area of the Gap	Themes for Future Research	PESTELS Factors	Discussion on the Themes
2. Technical limitations of IoT and blockchain technology association	1.4. Decentralization should be optimized and maximized [4,7,23]	P Soc. T	Code should be open source Decentralization of all levels of the project ecosystem to maintain the essential properties of BCT. Security and scalability should be adequately maintained [25].
	1.5. Interoperability between different blockchains [7,22]	T	Different blockchain protocols would need to be seamlessly interoperable within the project ecosystem. Interoperability projects to consider: Interledger [53], Cosmos [52], Polkadot [54], Oracles or APIs [56] would need to be practically tested for the data value chain of BECOM projects.
	1.6. Energy efficiency for an environmentally sustainable ecosystem [7,22,23].	Econ T Env	Energy efficient consensus mechanisms like PoA and PoS should be tested for suitability. Energy comparison analysis with traditional ERPs and centralized databases should be explored in future research.
	1.7. Computational requirements of the DDTC ecosystem.	T	Decentralized IT systems and decentralized computing [33] would need adequate capacity for the computational requirements of a DDTC ecosystem.
	2.1. Resource constraint IoT devices cannot run blockchain nodes	T	Further research on the wider-scale use of master blockchain nodes at the edge, using fog computing [61], in combination with light nodes.
	2.2. IoT devices identity and data authentication [7,22]	T	Further research on the wider-scale use of crypto hardware (Riddle & Code) [38] and microchips giving a unique cryptographic identity to the IoT device.
	2.3. IoT network management [9,22,23,59]	P T	Decentralized networks of blockchain validator nodes for IoT such as INCUBED [59] should be tested for the requirements of the DDTC ecosystem.
3. BIM and blockchain challenges	3.1. BIM data storage and BCT limitations [15,23]	T	Storage solutions mapping cloud storage to BCT through DHT [23] should be tested for the requirements of the DDTC ecosystem. Decentralized storage [35] and distributed storage—i.e., Swarm [36] and IPFS [37]—would need to be adequately scalable for the storage requirements of the DDTC ecosystem.
	3.2. Data structure requirements for the integration of BCT with BIM [30].	T	BIM data, Industry Foundation Classes (IFC) and BuildingSMART Data Dictionary (bsDD) need to be integrated with BCT data structure in a standardized way.
4. Digital twin data challenges with blockchain	Integration of blockchain with DT data [21,26]	P T	The data value chain of the DDTC ecosystem need to be integrated with BCT in a format agnostic way. The data should be managed in accordance with <i>The Gemini Principles</i> [19] Data privacy requirements [22].
5. Complexity of projects lifecycles	Lifecycle and Circular Economy [6,7,9,21,26]	Env	Further research is needed to evaluate the feasibility, cost/benefits and environmental analysis for materials traceability, inventory, recycling, and reuse throughout the lifecycle of the DDTC smart asset.

The suitability and limitations of the DDTC framework for the BECOM industry 4.0 can then be evaluated against these gaps; and future research directions are also identified in this section.

The governance of decentralized blockchain networks is a key challenge. Unlike previous studies, the DDTC model proposes using a combination of the private, consortium, and public blockchain networks to narrow this gap. These three networks would then comprise the core elements of the back-end blockchain layer, as shown in Figure 2. These blockchain networks have different levels of governance (private, consortium, and public) adapted to the group level they respectively refer to (enterprise, project, or public) as discussed in Section 5. These blockchain networks should be interoperable with each other to enable connectivity within the ecosystem. Essential project data can be anchored or bridged from an enterprise-level private blockchain to a common project-based consortium blockchain facilitating transactions between project-wide stakeholders in a secure and interoperable manner. Private and consortium blockchains can use efficient consensus mechanisms such as proof-of-authority (PoA) [44], which is scalable, energy-efficient, and has minimal transaction fees. Additionally, the PoA consensus mechanism can ensure role-based access control, a key requirement for DT ecosystems [17]. However, the suitability of PoA consensus mechanisms for the functional and non-functional requirements of blockchain applications for the BECOM industry data value chain would need to be practically verified by further research works. Private and consortium blockchains networks data can be anchored into public blockchains when it is required to make key project information auditable by the public in order to improve trust, transparency, and integrity of the data. As shown on Figure 2, the blockchain layer of the DDTC model includes public blockchains as a key component. These public networks should have sufficient throughput; hence, platforms such as Ethereum 2.0 [45], Cardano [47], or Solana [65] could be explored for future experimentations. Indeed, these public blockchain platforms use proof-of-stake (PoS) (and proof-of-history (PoH) for Solana) consensus mechanisms, that are respectively called Casper [46] (for Ethereum 2.0) and Ouroboros [48] (for Cardano). These efficient consensus mechanisms are significantly more scalable and energy efficient than PoW mining. Moreover, these public blockchains integrate native cryptocurrencies [60] that enable incentivization for participants to ‘play by the rules’. They also integrate smart contracts to automate processes such as payments, purchase orders, contracts, decentralize the funding of construction projects (Li et al., 2019), and enable the tokenization of digital or physical assets. Alternatively, with less scalable blockchain such as Ethereum 1.0 [32], transactional data and states can be anchored on the blockchain by packet at regular time intervals. This method is viable to overcome scalability limitations for the Exonum and Stadgerspas projects [40]. Additionally, layer two “off-chain” scaling solutions like Plasma [66] or Raiden Network [67] can overcome the scalability limitations of public blockchain with low throughput such as Ethereum 1.0.

Regarding the blockchain interoperability challenges revealed in Table 3, the DDTC model proposes to leverage interoperability protocols such as Interledger [53], Cosmos [52], and Polkadot [54] to overcome interoperability issues. To integrate BCT with IoT, the DDTC aims to extend the decentralization of IoT management with protocols like INCUBED [59]. Additionally, IoT devices’ identity and data authentication can be secured with crypto hardware [20] secure elements [38].

Data storage limitations of BCT form a major gap and key challenge making it impossible to process large volumes of data (from BIM, IoT, or DT) on the blockchain. To narrow this gap area, the DDTC model suggests as a first approach to leverage DHT to map resilient data storage systems with blockchain hash proofs [26]. However, this approach is limited because the actual data would remain off the blockchain, and only its digital fingerprint would be on the blockchain. Hence, decentralized database [24] and decentralized cloud storage [35] blockchain-based systems should be considered to enable the decentralization and security of data storage for DTs. Moreover, distributed storage systems like IPFS [37] and Swarm [36] that use DHT can also be used. However, these DHT based distributed storage platforms have limited storage capacity and do not facilitate data privacy. These limitations make them potentially inadequate for the Big Data volume and privacy requirements of the information value chain from projects of the BECOM industry.

The integration of blockchain with cyber-physical systems (BCPS) like DT is another gap area since these technologies are emerging and the literature and practical implementations in this field are scarce. The DDTC model is a BCPS [22] with four layers that include a blockchain layer, a computing layer, a data management layer, and a connection layer. The back-end computing layer is composed of blockchain protocols (including open-source public blockchains), smart contracts, DApps, DAOs, DHT, oracles, interoperability protocols, decentralized cloud computing systems, distributed storage systems, access control mechanisms, edge and fog computing, and privacy layers as required. The role of DDTC connection layer is to capture project data from the 'real world' via IoT and oracles, and from software via APIs. These data are initially filtered in accordance with *The Gemini Principles*, and transferred from the connection layer to the data management layer. The DDTC data management layer ensures that information management also follows *The Gemini Principles* using, for example, data cleansing, data curation, data structures, data mining, data modeling, and data analytics techniques, so that the data volume decrease while the data value is increased [19]. Moreover, this decrease in data volume is beneficial for the storage limitation of BCT and contributes to filtering the data so that only valuable data are anchored on the blockchain. The data privacy requirements for BECOM project forms a gap when it comes to public or consortium blockchains. Indeed, consortium and public BCT are open to multiple stakeholders and data privacy and confidentiality of transactions can be a challenge. Moreover, the GDPR privacy right to erasure [28] is not well compatible with BCT since certain project data may not need to be retained after the project life cycle end. Hence, public blockchains would not be fit for the purpose of specific data requiring to be deleted at a certain point in time. Future research works should define the identification and categorization of project data requiring to be deleted or to remain permanently stored. The DDTC model aims to address the privacy requirement with the components of the private blockchain of the core blockchain layer. Indeed, the enterprises and stakeholders that require to keep certain data private would simply not transact them publicly and transact them only through their private blockchain networks. Alternatively, privacy protocols or encryptions mechanisms may be explored, as mentioned in Section 4.

The DDTC model is beneficial for BECOM projects as it can increase efficiency, productivity, transparency, trust, and security for the project data value chain. The DDTC is cyclic to integrate the CE and improve sustainability by reducing construction wastes and facilitating reuse and recycling through the traceability of materials enabled by BCT [64] throughout project lifecycles. The DDTC also provides a transparent (or private as needed), traceable, and secured unified information management framework that can address the complexity of data management at all phases of BECOM projects and contribute to reducing data silos in the industry. Furthermore, the DDTC model can integrate decentralized finance (DeFi) protocols [68] by leveraging smart contracts and allowing projects participants and the public to exchange value securely in a trustworthy and peer-to-peer way, with the financial ecosystems of smart assets represented by their DTs. The combination of DeFi with the CE can lead to the formation of a decentralized CE (DeCE) which could be the object of future research works. In a fully decentralized context, the DDTC model could run along with DAOs [9] to automate organizations' processes in the back-end of DT applications. Peer-to-peer blockchain networks can also facilitate decentralized collaborations between key project stakeholders such as clients, engineers, architects, contractors, regulators, facility managers, and owners. Moreover, BCT would secure the sharing of information within DCDEs that record historical data throughout the lifecycle of projects. Common data environments (CDE) could be "distributed across different computers" [63], acting as blockchain nodes and recording information historical states changes within the CDE [69], and hence forming a DCDE [9]. Such a distributed collaborative environment could span from the project information model (PIM) to the asset information model (AIM) and cover the full lifecycle of smart infrastructure assets. Big Data from the project information value chain would be managed in accordance with *The Gemini Principles* [19] before they are stored on DCDEs. The DDTC model also considers strengthening the implementa-

tion of reforms and regulations within the industry through the integration of regulatory blockchain nodes validating key transactions throughout the lifecycle of projects.

This study provides the novel DDTC framework, its technological components, and the key technological gaps identified. Hence the theoretical implications of this study are for industry practitioners to develop the theoretical framework further, standardize it, and contribute to closing the gaps. The DDTC provides the key technological building blocks for the adoption of BCT for DT in order to improve some key challenges of the BECOM industry. Hence the practical implications of this study will contribute to enhancing the BECOM industry 4.0 with the DDTC model that aims to facilitate trusted collaborations, improve information sharing, enhance information management [7] and security, and promote environmental sustainability. The DDTC model promotes the integrity of the data value chain and can guarantee the trustworthiness of the information that is handed over at each phase of the project lifecycle. The DDTC model is decentralized and contributes to a paradigm shift towards a democratization of the BECOM industry by redistributing control to individuals [7] through the decentralization of services and the disintermediation of centralized third parties. This decentralized model leverages incentivized data sharing in a peer-to-peer way to reduce the adversarial behaviors in the BECOM industry that are limiting collaboration and information sharing. This paradigm shift also leverages automation of processes with smart contracts to improve costs savings, efficiency [7], and productivity. The DDTC model improves safety [2], transparency, cybersecurity, information integrity, openness, and environmental sustainability for the BECOM industry. Finally, the DDTC is beneficial for the industry and the public good; and it creates value, provides smart insights, and is aligned with *The Gemini Principles* [19].

7. Conclusions

The paper has developed a framework for the integration of BCT with DT for BECOM projects in the context of industry 4.0. The three objectives were to identify the challenges of the BECOM industry 4.0 affecting BCT adoption, evaluate the key technological factors affecting the adoption of BCT, and propose a conceptual model facilitating the integration of BCT and DT for projects of the BECOM industry 4.0. The originality of this paper comprises the proposed technological framework based on a novel conceptual model called the decentralized digital twin cycle (DDTC). This model promotes ecosystems of trusted, decentralized, and sustainable DTs for the BECOM industry 4.0 where BCT secures information sharing for the data value chain of projects. Moreover, the DDTC model contributes to narrowing the technological gaps identified about BCT adoption for DT for industry 4.0.

The key challenges, affecting BCT adoption in the industry, that were identified from the PESTELS review of the literature are the lack of trust, lack of transparency, lack of traceability of information, inefficiencies, blockchain networks governance, lack of collaboration, fragmentation in data silos, high implementation costs, lack of productivity, adversarial practices, poor digitization, cybersecurity risks, difficulties enforcing standards and regulations, lack of accountability, data interoperability, blockchain interoperability, and environmental sustainability. The key technological factors affecting BCT adoption in the BECOM industry 4.0 relate to the decentralization of systems and networks, stringent requirements for Big Data, specific IT requirements for BCT, integration of smart contracts, identity management and access control, blockchain properties and performances, and the integration of BCT with the key technologies of the BECOM industry 4.0: BIM, IoT, and DT.

Another originality of the paper is the identification of technological gaps affecting BCT adoption for DT in the BECOM industry 4.0. The gaps areas identified in the literature are: the technical and non-functional requirements for BCT applications in the BECOM industry 4.0, and the technological challenges related to the integration of BCT with BIM, IoT, and DT throughout complex projects' lifecycles.

The DDTC model leverages BCT to strengthen the data value chain in terms of data sharing, cybersecurity, data integrity, immutability, traceability, and transparency or

privacy of information. The DDTC model can reduce data silos in the BECOM industry by leveraging decentralization of IT infrastructures. This decentralization is achieved with key technological components, such as DCDEs, to enhance collaboration and information sharing, smart contracts, DApps, DAOs, decentralized storage systems, decentralized cloud computing systems, decentralized management of IoT networks, decentralized oracles, and decentralized governance for blockchain networks. Project stakeholders (consultants, engineers, architects, contractors, regulators, facility managers, owners, and users) can share transactional data in a peer-to-peer way and validate transactions on the blockchain shared ledger to ensure data integrity. The security and integrity of IoT data are enhanced with crypto hardware to cryptographically secure IoT devices' identities and ensure the authentication of IoT data. Thus, the DDTC framework ensures that the sensors' data input is secure and trustworthy. To overcome data storage limitations of BCT, the Big Data volumes involved throughout BECOM projects can be stored in decentralized cloud storage and mapped to the blockchain through DHT. The model considers inter-blockchain solutions to address interoperability challenges. Smart contracts are leveraged for automation of processes in order to reduce time and costs and improve efficiency and productivity in the BECOM industry 4.0. Efficient consensus mechanisms (e.g., PoA and PoS) are proposed for adequate scalability of the blockchain layers that require high throughput and low latency for high data velocity. Moreover, such consensus mechanisms are energy efficient to minimize the project's carbon footprint. Additionally, the DDTC model is cyclic to promote sustainability and minimize waste by reusing and recycling materials for the CE and the DeCE. Hence, the DDTC technological framework proposed addresses some key industry challenges and technological factors, and it contributes to narrowing the gaps identified in the literature.

This paper is limited to examining the current literature and state of the art on blockchain technology and its applications for DT in the BECOM industry 4.0. Future studies are suggested including practical experiments for implementing the proposed framework requiring to be developed and tested. The future studies which are experimentation based can reveal and validate that sufficient scalability, energy efficiency, and cost savings can be achieved with blockchain protocols adequately chosen for DTs of the BECOM industry 4.0. Moreover, the blockchain consensus mechanisms discussed in this paper should be tested with high data volume, velocity, and variety that simulate the real conditions of the data value chain from a project of the BECOM industry 4.0. Thus, future works should test if BCT can perform adequately in terms of scalability, energy efficiency, cost (infrastructure deployment cost and transaction fees), as well as the integration of BCT with other key technologies like BIM, IoT, and DT. Additionally, future research studies should work on the classification of project information to identify the data categories (from the BECOM projects information value chain) that require the most to be anchored in the blockchain layer (private, consortium, or public) of the DDTC. Future work should also identify the categories of project data that require security, transparency, privacy, openness, immutability, deletion, or anchorage into the blockchain for each phase of the project lifecycle. Furthermore, future research is required to develop open data standards to standardize key project data schemas and enable a structured data layer to integrate project data, BIM data, IoT data, DT data, and asset information into the blockchain. Additionally, the standardization for the project information value chain would require compliance with *The Gemini Principles*. Finally, future works should investigate the decentralization of collaborative financial ecosystems in the BECOM industry 4.0 and its integration to the CE to form a DeCE.

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Abbreviations

AEC	Architecture, engineering and construction
AIM	Asset information model
API	Application programming interface
BCT	Blockchain technology
BCPS	Blockchain with cyber-physical systems
BECOM	Building, engineering, construction, operations, and mining
BIM	Building information modelling
bsDD	BuildingSMART data dictionary
CDE	Common data environment
CE	Circular economy
DCDE	Decentralized common data environment
DeCE	Decentralized circular economy
DDTC	Decentralized digital twin cycle
CAD	Computer-aided design
COBie	Construction operations building information exchange
CPS	Cyber physical system
DAO	Decentralized autonomous organizations
DApp	Decentralized application
DeFi	Decentralized finance
DHT	Distributed hash table
DT	Digital twin
FM	Facility management
GDPR	General data protection regulation
GIGO	Garbage in garbage out
GIS	Geographic information system
IFC	Industry foundation classes
IoT	Internet of things
IPFS	The interplanetary file system
IT	Information technology
PoA	Proof of authority
PoS	Proof of stake
PoW	Proof of work
PESTELS	Political, economic, social, technological, environmental, legal, and security
PIM	Project information model
RFID	Radio-frequency identification
UI	User interface
XML	Extensible markup language

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