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REVIEW ARTICLE

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Examining the nexus of blockchain technology and digital twins: Bibliometric evidence and research trends

Abstract The integration of Blockchain Technology (BT) with Digital Twins (DTs) is becoming increasingly recognized as an effective strategy to enhance trust, interoperability, and data privacy in virtual spaces such as the metaverse. Although there is a significant body of research at the intersection of BT and DTs, a thorough review of the field has not yet been conducted. This study performs a systematic literature review on BT and DTs, using the CiteSpace analytic tool to evaluate the content and bibliometric information. The review covers 976 publications, identifying the significant effects of BT on DTs and the integration challenges. Key themes emerging from keyword analysis include augmented reality, smart cities, smart manufacturing, cybersecurity, lifecycle management, Ethereum, smart grids, additive manufacturing, blockchain technology, and digitalization. Based on this analysis, the study proposes a development framework for BT-enhanced DTs that includes supporting technologies and applications, main applications, advantages and functionalities, primary contexts of application, and overarching goals and principles. Additionally, an examination of bibliometric data reveals three developmental phases in cross-sectional research on BT and DTs: technology development, technology use, and technology deployment. These phases highlight the research field's evolution and provide valuable direction for future studies on BT-enhanced DTs.

Keywords blockchain technology, digital twin, literature review, bibliometric analysis, research trend

1 Introduction

With the increasing digitization of society, the virtual cyberspace continues to expand, offering a range of digital solutions, including Digital Twins (DTs) and the metaverse, to enhance work and living environments. DTs, in particular, are virtual models that replicate the characteristics, behaviors, and interactions of physical entities in real or near real-time. Since their inception almost 20 years ago, DTs have been widely implemented across various industries (Grieves, 2019; Semeraro et al., 2021). However, they face challenges such as data exchange issues, unclear product attributes, and susceptibility to cyber-attacks, which hinder their full potential (Hakimi et al., 2024; Salvi et al., 2022; Barricelli et al., 2019). Blockchain Technology (BT), being an innovative technological advancement, offers significant potential to enhance the applications of DTs. Its decentralized and immutable nature as a digital ledger ensures data integrity, fosters efficient information exchange, and eliminates intermediaries (Suhail et al., 2022a; Islam et al., 2020). Within the context of Industry 4.0, the integration of BT with DTs has emerged as a primary driver of technological innovation (Chen et al., 2023; Suvarna et al., 2021). For example, Wang et al. (2023) proposed a method to maintain data flow in dynamic DT models using BT. Meanwhile, Yan et al. (2022) showcased how BT enables secure and decentralized operations in energy facilities. Moreover, Akash and Ferdous (2022) emphasized the role of BT in

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safeguarding security and privacy in healthcare DT systems. In the field of construction, BT-based smart contracts are employed to establish performance standards and ensure the quality of building DTs (Hunhevicz et al., 2022). Notably, Suhail et al. (2022a) and Yaqoob et al. (2020) conducted reviews that focused on the exploration of BT applications in DTs, employing qualitative analysis to scrutinize fewer than 20 studies. Given the rapid expansion of this research area, it is crucial to acquire more comprehensive evidence to gain a holistic understanding and map the knowledge domain effectively.

Despite the abundance of publications at the intersection of BT and DTs, a comprehensive review of this research field is still lacking. A holistic interpretation of existing studies in this domain can deepen our comprehension of BT's applications within DTs, foster further integration of these technologies, and offer valuable insights for future research on BT-enhanced DTs. Additionally, a thorough analysis of the bibliographic data from these studies is crucial to determine the current landscape, discern development trends, and identify emerging areas of interest. To bridge this research gap, this review study adopts a hybrid qualitative and quantitative approach to interpret the cross-sectional research on BT and DTs. Specifically, this study aims to address the following research questions (RQs):

RQ1: What is the development trend of the cross-sectional research on BT and DTs?

RQ2: What are the key impacts of BT on DTs and how do they materialize?

RQ3: What are the major challenges to integrate BT into DTs and implementing BT-enhanced DTs?

RQ4: What are the hotspots and major subjects in the cross-sectional research on BT and DTs?

RQ5: What are the citation relations of studies regarding the strength and timelines of the citation bursts, and how do they impact the development trend of the research?

This study is organized into seven sections. Following the introduction (Section 1), Section 2 provides an overview of the research background on DTs and BT. Section 3 describes the methodology, including the review approach, procedures, and guiding principles. In Section 4, the study presents its findings and analyses, with a focus on bibliometric evidence. Section 5 explores the evolution and trends in research, highlighting current gaps and suggesting areas for future investigation. Section 6 discusses the theoretical and practical contributions of this review. Section 7 concludes the study by summarizing the key findings, contributions, and acknowledging the study's limitations. This review contributes to the cross-sectional study of DTs and BT by offering a comprehensive survey of the field, identifying areas for future research, explaining how BT enhances DTs, and categorizing the primary challenges that require further exploration.

2 Research background

2.1 DTs

DTs have emerged as a significant research topic in informatics, often described as information models that closely mimic corresponding physical entities to simulate and conceptualize their components, functions, characteristics, and properties (Grieves, 2019; Semeraro et al., 2021). By utilizing digital models, sensors, and related data, DTs improve product development, work management, and overall quality of life (VanDerHorn and Mahadevan, 2021). Although initially introduced in the manufacturing industry, DTs now find applications in various scenarios, supporting different human-computer interactions and cyber-physical systems (Grieves, 2019; Rantala et al., 2023; Jones et al., 2020). The terminology related to DTs includes similar concepts such as mirrored space models (Grieves, 2005b), information mirror models (Grieves, 2005b), and digital shadows (Abele et al., 2016). In this study, we refer to 'digital twin(s)' and these analogous terms collectively when searching for DT-related studies.

2.2 BT

BT, based on distributed ledger technology, enables decentralization, transparency, immutability, and security in information management. It achieves this by encrypting data through blocks using the Hash algorithm and securely recording transactions across multiple nodes using cryptographic methods (Rajasekaran et al., 2022; Huynh-The et al., 2023). There are three types of blockchains: public, federated, and private, which are designed to meet the diverse requirements of management agents in organizations with different levels of decentralization (Casino et al., 2019). With the incorporation of consensus mechanisms and programming logic, BT can also facilitate the implementation of smart contracts (Vacca et al., 2021). Initially emerging in the financial sector, BT has since expanded its reach to various other work and life contexts. It has gained particular significance in the supply chain and logistics domain, where it improves supply chain transparency, performance, and mitigates the risk of logistics failure (Liu et al., 2023b; Fosso Wamba et al., 2020; Zhang et al., 2022). BT also plays a crucial role in driving sustainable development (Di Vaio et al., 2023; Du et al., 2022) and finds diverse applications across sectors such as healthcare (Stafford and Treiblmaier, 2020), tourism (Valeri, 2020), and public management (Treiblmaier and Sillaber, 2020). Moreover, BT is leveraged in various scenarios, including city administration (Bhushan et al., 2020), combating deception and misinformation (Chen et al., 2020), facilitating information sharing (Zheng et al., 2018), enhancing online education (Alammary et al., 2019), advertising and marketing (Rejeb et al., 2020), and patent management (Denter et al., 2023). As a key infrastructure component, BT plays a critical role in improving the efficiency of information management.

2.3 Integrating BT into DTs

DTs are increasingly recognized as essential components within information systems, significantly enhancing the interaction between computers and humans (Cimino et al., 2019; Dietz and Pernul, 2020; Qi et al., 2021). DTs are designed to create real-time virtual replicas of physical objects or systems for monitoring, analysis, and optimization purposes. However, their practical implementation faces challenges such as data interoperability, privacy concerns, and property rights issues (Hakimi et al., 2024; Rantala et al., 2023; Salvi et al., 2022). The integration of BT into DTs offers a promising solution to these challenges, while also enhancing the potential for more advanced implementations.

The integration of BT with DTs, commonly known as BT-enhanced DTs, is a widely adopted application that enhances the functionalities of DTs. BT contributes to DTs by providing secure data storage, ensuring data integrity through immutability, facilitating transparent data exchange among multiple stakeholders, and fostering trust within the DT ecosystem (Suhail et al., 2022a; Upadhyay, 2020). Furthermore, the application of BT ensures data security and virtual property rights in the Metaverse (Huynh-The et al., 2023). Additionally, BT use enhances various smart operations and productions, such as smart cities (Bhushan et al., 2020), smart healthcare (Akash and Ferdous, 2022), and smart manufacturing (Lupi et al., 2023). BT also enhances the cyber-physical system (CPS) by guaranteeing secure traceability, compliance, authenticity, quality, and safety, thereby playing a crucial role in advancing Industry 4.0 (Suvarna et al., 2021). Moreover, integrating BT into DTs enhances decentralized governance and promotes efficient and sustainable industrial practices (Yaqoob et al., 2020). It is crucial to conduct a systematic analysis of the intersecting research fields of DTs and BT in order to identify challenges in BT integration, chart the evolution of this research domain, and offer insights for the implementation of BT-enhanced DTs.

3 Methodology

3.1 General research approach

A systematic approach is essential for thoroughly examining existing literature and gathering pertinent data, thereby facilitating the development of comprehensive insights within a specific research domain (Bhatti et al., 2021; Islam et al., 2020; Chan et al., 2018). This review follows the preferred reporting items for systematic reviews and meta-analysis (PRISMA) principles for study selection and screening. Additionally, the CiteSpace software is used to conduct a bibliometric analysis of the selected studies. The analyses conducted using CiteSpace involve the visualization and examination of bibliometric data, the elucidation of co-citation relationships among studies, and the extraction of insights regarding research trends, emerging topics, and the overall framework of the research field (Chen, 2016). The methodology adopted in this review is depicted in Fig. 1. The incorporation of PRISMA principles ensures a rigorous review process, while the application of CiteSpace enhances the quality of the bibliometric analysis. The findings drawn from this review are based on a synthesis of the literature and the results obtained from both the qualitative content analysis of the studies and the quantitative analysis of their bibliometric data.

3.2 The systematic review process with PRISMA

The PRISMA principles provide a structured approach for conducting systematic reviews. This includes defining eligibility criteria and search strategies, extracting relevant studies and data, applying data analysis techniques, and identifying potential bias in the analysis (Liberati et al., 2009; Moher et al., 2010). The following subsections describe how these PRISMA principles were applied in this review.

3.2.1 Eligibility criteria and search strategy

Scopus, Web of Science (WoS), IEEE Xplore, and ACM Digital Library are widely recognized as leading databases for indexing research in information technology and computer science (Bar-Ilan, 2018; De Sutter and Van Den Oord, 2012; Labbé and Labbé, 2013). These databases are commonly used for systematic literature reviews in IT-related domains, as demonstrated in studies such as those by Soares do Amaral et al. (2022), Gaikwad et al. (2021), and Camacho and Alves-Souza (2018). For this review, these four authoritative academic databases were utilized, focusing on journal articles and conference papers/proceedings for their credibility. The search included specific keywords such as "blockchain*" (or variants like "block chain*" or "block-chain*") and "digital twin*" (or "mirror space model*" or "information mirror model*" or "digital shadow*"). These keywords targeted the Topic/Title-Abstract-Keywords/Meta-Data fields to ensure the relevance of the retrieved studies. This approach excluded the full texts to avoid irrelevant results as some studies may mention blockchain technology or digital twin tangentially, thus adding noise to the data. The eligibility criteria for inclusion were as follows: 1) studies had to be journal or conference papers, including

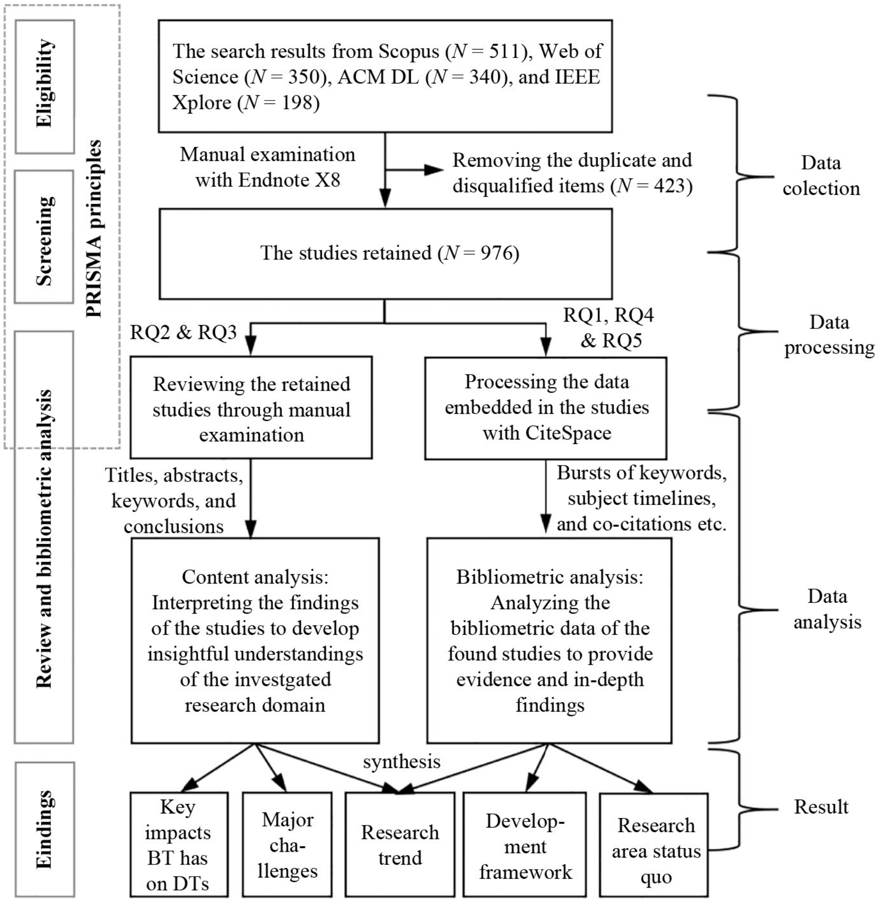


Fig. 1 The research approach of this review study.

reviews and proceedings indexed by at least one of these databases; 2) they needed to be published in English; 3) BT and DT had to be featured in the title, abstract, keywords, or as a primary focus; and 4) complete bibliometric information should be available for further analysis.

3.2.2 Data extraction and processing

The process of data extraction, as depicted in Fig. 1, involved manual examination. Initially, the search results from the four databases were compiled, and any duplicate or ineligible items were filtered out based on the pre-defined eligibility criteria. To address potential overlap of search results across different databases, Endnote X8 software was employed to identify and remove duplicates. Additionally, a rigorous manual review was conducted to ensure that all retained studies fulfilled the established eligibility criteria. Following this process, a total of 976 studies were selected for subsequent analysis.

3.2.3 Content analysis

The content analysis of the selected studies was conducted using both manual examination and CiteSpace for keyword and citation burst analysis. This comprehensive approach was employed to determine the primary effects of BT on DTs and identify the main challenges associated with integrating BT into DTs. The findings from this content analysis were pivotal in addressing RQ2 and RQ3.

3.2.4 Bibliometric analysis

Bibliometric analysis employed CiteSpace to gain deeper insights into the intersectional research on BT and DTs. This analysis included keyword burst analysis, subject timelines, and co-citation assessments, following methodologies used in studies by Li et al. (2017) and Sood et al. (2022). The insights obtained from this bibliometric analysis were instrumental in addressing RQ4 and RQ5.

3.2.5 Possible bias

Potential bias might arise from the search method, as it did not cover the entire literature related to the topic. An exploratory search on WoS using the query "'TS= (("blockchain" or "block chain" or "distributed ledger") and ("digital twin*" or "internet of things" or "IoT" or "BIM" or "building information model*" or "city information model*" or "cyber-physical system" or "CPS" or "predictive manufacturing" or "predictive maintenance"))'" yielded numerous irrelevant studies that went beyond the scope of this research. It proved impractical to manually sort through these studies. Therefore, to reduce the risk of introducing additional bias, this study followed the research approach outlined earlier.

4 Analyses and findings

4.1 Development trends in the cross-sectional research on BT and DTs

RQ1: What is the development trend of cross-sectional research on BT and DTs?

Figure 2 shows the progression of publication frequency in cross-sectional research on BT and DTs after removing duplicated copies. The search conducted on October 16, 2023, resulted in a total of 976 publications, indicating a persistent upward trend in this research field. Analysis of annual publication frequencies reveals a consistent and rapid expansion in cross-sectional studies of BT and DTs. The years 2015–2016 mark the initial stage of this research domain, with publication counts in single digits (2 and 7, respectively). Subsequently, the field experienced a significant surge, with the number of publications doubling in 2017, 2019, and 2022, highlighting robust and continuous growth.

4.2 BT's key impacts on DTs

RQ2: What are the key impacts of BT on DTs and how do they materialize?

4.2.1 Enabling decentralized or self-organized management with DTs

One of the primary motivations for integrating BT into DTs is to enhance decentralized or self-organized management. Li and Kassem (2021) developed a DT-based information system fortified with BT to improve collaborative performance, resource planning and supply, and to support cooperative manufacturing with reliable information. Additionally, BT is effectively employed in CPSs to secure efficient information exchange within virtual cyberspace, thereby facilitating intelligent manufacturing (Suvarna et al., 2021; Wan et al., 2022). In the realm of the increasingly popular metaverse, BT empowers participants in the virtual DT environment to engage cooperatively in a decentralized manner, navigating and experiencing new dimensions of e-life (Beniiche et al., 2022; Chen et al., 2023; Santana and Albareda, 2022).

This review notes that the decentralization enabled by BT is frequently linked with the application of smart contracts. Leng et al. (2020b) innovatively employed smart contracts in the ManuChain project to boost collaborative efficiency in intelligent manufacturing. This approach utilized DT visualization and automated manufacturing strategies for enhanced collaborative work. A similar implementation was observed in aiding manufacturing producers to establish Decentralized Autonomous Organizations (DAOs) using a combination of smart contracts and DTs (Leng et al., 2019). In the construction industry, the integration of smart contracts with DTs has been recognized as a means to advance decentralization and automation (Hunhevicz et al., 2022).

The influence of BT on decentralization and self-organization has received considerable attention in DT research within the manufacturing industry. However, this focus extends to other areas, including construction management and the metaverse domains. In these fields, research frequently utilizes DAOs to facilitate efficient information management, leveraging both BT and DTs.

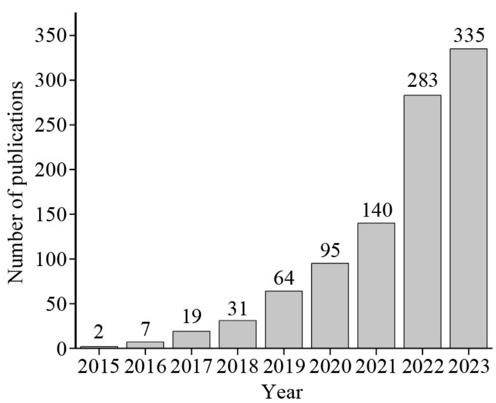


Fig. 2 Development trend of cross-sectional research on BT and DTs.

4.2.2 Guaranteeing security in the information management of DTs

BT plays a pivotal role in enhancing security within DT information management. Putz et al. (2021) showcased the application of BT within the framework of DAOs to bolster the security of DT models. Furthermore, Suhail et al. (2022b) illustrated this concept through the case of smart automobiles, underscoring the significance of BT-enhanced DTs in securing CPS. The effectiveness of BT in safeguarding DT-based systems has been substantiated across various technological contexts, including the industrial internet-of-things (IIoTs) (Gajek et al., 2021), space information network systems (Zhuo et al., 2021), and building information systems (Li et al., 2022). The influence of BT on DTs aligns with its foundational role as a cybersecurity technology and remains a vibrant area of ongoing research.

4.2.3 Providing credibility to DT-related information

Some studies have investigated the impact of BT on credibility and information exchange in the context of DTs. For example, Lu et al. (2021) examined how integrating BT with edge computing can enhance DT applications. Other research has focused on BT's influence on model-based collaboration and development processes. This includes exploring the visualization of BT-enhanced DT environments (Kanak et al., 2019), improving pandemic alerting collaboration using BT-enhanced DTs (Sahal et al., 2022), and developing DT models that benefit from BT-facilitated information sharing (Hasan et al., 2020). Moreover, BT has been shown to enhance value co-creation in the supply chains of DT products by ensuring information transparency (Berneis and Winkler, 2021; Kamble et al., 2022; Wang et al., 2022). Additionally, BT aids in incorporating relevant information into DTs within the business context, thereby enabling a more accurate representation of real-world conditions (Alles and Gray, 2020).

4.2.4 Facilitating systematic information exchange and integration of DTs

A significant body of research explores the use of BT to enable systematic information exchange and support the integration of DTs. BT's ability to authenticate and ensure the reliability of information plays a crucial role in enhancing systematic information exchange for integration activities among DT users. This includes areas such as multi-agent collaboration (Sahal et al., 2021), interoperable simulation for decision-making (Bruzzone et al., 2019), the integration of various internet of things (IoT) applications (Mazzei et al., 2020), and the development of BT-enhanced information systems incorporating DTs (Jiang et al., 2021). However, it should be noted that further progress in integrating BT into DTs requires the support of additional technologies, as discussed by Lu (2021).

Several studies highlight the use of BT to enhance information exchange in CPS. Specifically, BT has been applied in two categories of CPSs: industrial CPS (Guo et al., 2020) and social CPS (Wang et al., 2021). However, the current research primarily focuses on industrial product manufacturing. In this context, BT, in conjunction with DTs, has been used to manage product information and data (Huang et al., 2020). Tao et al. (2022) argue that BT can significantly improve the efficiency of DTs in optimizing collaborative workflows and manufacturing services. For example, in aircraft production, the integration of BT-enhanced manufacturing with DTs has yielded impressive results in terms of quality and reliability (Mandolla et al., 2019). Furthermore, the innovative application of BT within DTs paves the way for predictive maintenance and smart manufacturing (Lee et al., 2020).

4.2.5 How BT contributes to DTs

The contributions of BT features to DTs are visually represented in Fig. 3, based on the interpretations discussed in the preceding subsections. Key features of BT, including distributed ledger, encryption algorithm, traceability, and data reliability, are coupled with various DT application scenarios and challenges. These include organizational information management, information and data security, information verification, and the enhancement of information systems within DTs. However, as indicated by the reviewed studies, several challenges still need to be addressed to fully realize these benefits.

Furthermore, the study explores how various blockchain-related technologies contribute to the application of DTs in addressing specific issues and maximizing the use of BT. Table 1 provides a synthesized overview of these findings, drawing from relevant literature. As shown in the table, the application of BT into DTs varies in different sectors and scenarios due to the characteristics of the contexts and the technological advantages of blockchain-based technologies.

4.3 Challenges to adopting BT in DTs and implementing BT-enhanced DTs

RQ3: What are the major challenges to integrate BT into DTs and implementing BT-enhanced DTs?

4.3.1 Lack of standards and cooperative strategies for implementing BT within DTs and BT-enhanced DTs

The integration of BT within DTs presents significant challenges due to the absence of standardized technical norms and collaborative strategies. The lack of technical standards and established protocols for cooperation poses considerable obstacles to the further advancement of BT within DTs (Mazzei et al., 2020). To facilitate seamless information exchange in BT-based CPS, the development of fundamental infrastructures with explicit specifications is crucial (Jiang et al., 2022; Suvarna et al., 2021). Moreover, industrial applications of BT-enhanced DTs require the adoption of standardization and alignment measures to overcome institutional hurdles (Leng et al., 2020a; Wishnow et al., 2019). Therefore, the progression of BT-enhanced DTs necessitates institutional frameworks that include both standardization and strategic alignment.

4.3.2 System inertia and organizational resistance against the disruptiveness of BT

Another significant challenge in the integration of BT within DTs is the systemic inertia and organizational resistance to the disruptive nature of BT in conventional practices. The transformational impact of BT, especially when combined with DTs, is profoundly altering industrial

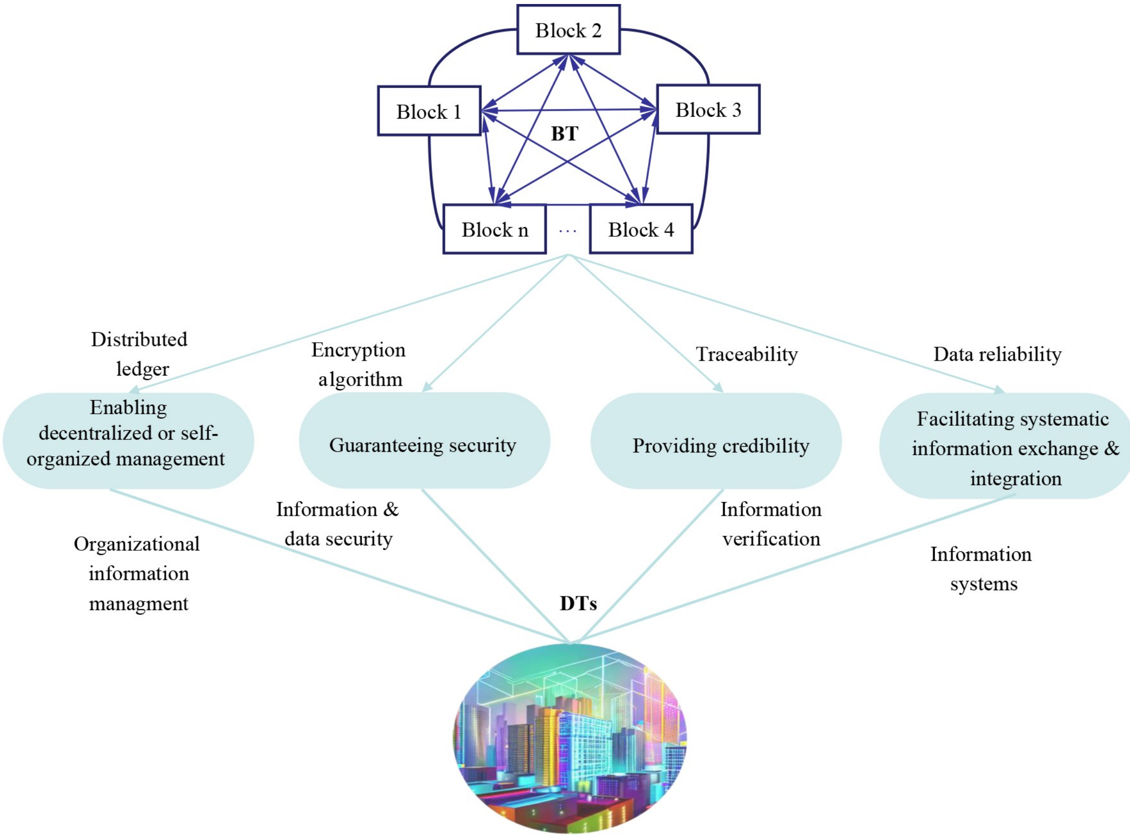


Fig. 3 How BT's features contribute to DTs.

Table 1 How different blockchain-related technologies contribute to DT application

DT application/issues	Blockchain-based technologies	Sectors/scenarios	References
Data security and property issues	Asymmetric cryptography	Manufacturing; healthcare; the metaverse etc.	Sasikumar et al. (2023); Stafford and Treiblmaier (2020); Huynh-The et al. (2023)
DT-based information systems	Distributed ledger	Construction; energy; manufacturing etc.	Yang et al. (2023); Singh et al. (2022); Kirli et al. (2022)
Miscellaneous delivery and checking procedures	Smart contract	Construction; energy; manufacturing etc.	Li and Kassem (2021); Leng et al. (2023); Kirli et al. (2022), Wu et al. (2023)
Data transfer and information exchange	Information encryption (e.g., timestamp, Hash algorithm)	Finance, food, construction, smart cities, etc.	Shi et al. (2023); Elghaish et al. (2023); Bhushan et al. (2020)
Multi-party collaboration and trust issues	Consensus mechanisms	Public management; the metaverse, construction etc.	França et al. (2023); Sasikumar et al.(2023); Scott et al. (2021)

norms (Wishnow et al., 2019). Collective adoption is critical for the efficacy of BT, and developing alignment strategies is necessary to mitigate systemic resistance to its disruptive effects (Leng et al., 2021). Despite these challenges, BT disruption is integral to advancing intelligent information management in business operations and supply chain management (Raj, 2021). Furthermore, Ding et al. (2021) explored the emerging governance model shaped by the use of BT, particularly in the context of DAOs, and identified governance deficiencies as an area requiring further exploration.

4.3.3 Maturity issue of BT use within DTs and BT-enhanced DTs

The application of BT within DTs across different industries and scenarios is hindered by varying levels of maturity. For example, in the context of food supply chains, the integration of BT in CPS faces challenges such as inadequate technical infrastructure and insufficient governmental support (Shi et al., 2023; Smetana et al., 2021). Furthermore, future industrial applications envision the utilization of BT-enhanced DTs for managing product lifecycles, a capability that is not yet fully developed (Leng et al., 2020a; Song and Zhu, 2022). Additionally, the juxtaposition of BT and DTs highlights a notable issue of technical immaturity, which limits their potential to effectively enhance information management (Nabeeh et al., 2022). Addressing these maturity challenges from an industry-level perspective, including promotion and governance, is crucial for deepening understanding of these issues and facilitating their resolution.

4.3.4 Possible burden on information management work and extra demand for resources

Implementing BT within DTs can introduce additional complexities and resource demands in information management. These challenges primarily arise from the operational characteristics of distributed ledger systems, which can result in latency during information processing and a heightened need for resources (Nikander et al., 2019). While blockchain-enabled distributed ledgers offer enhancements in production and supply chain efficiency, they also require additional operational efforts and resources in industrial settings (Smetana et al., 2021). However, the integration burden of blockchain-enabled distributed ledgers might be mitigated as digital industrial environments evolve to more effectively accommodate their application (Leng et al., 2020a; Nabeeh et al., 2022; Song and Zhu, 2022). To address these challenges, further managerial research is essential in developing strategies for efficient implementation and resource management.

4.3.5 Challenges to implementing BT-enhanced DTs in different sectors and scenarios

Challenges related to the implementation of BT-enhanced DTs have been identified in existing research, and many of them are context-specific. In the manufacturing sector, BT-enhanced DTs face challenges in technology integration, security issues, and standardization problems (Leng et al., 2023; Lupi et al., 2023; Tao et al., 2022). In the healthcare sector, the implementation of BT-enhanced DTs involves managing the protection of personal privacy, fostering cooperation among different institutions, and adhering to medical practice codes (Akash and Ferdous, 2022; Stafford and Treiblmaier, 2020). In the energy sector, BT-enhanced DTs can help realize the distributed energy system, but due to the complexity of the energy market, the integration of the energy supply chain and the current system requires substantial efforts to realize (Bhatti et al., 2021; Abou El Houda and Brik, 2023; Kirli et al., 2022). The barriers in the construction sector to utilizing BT-enhanced DTs stem from its segmented nature and information isolation, which require more specifications of data and standardized practices to enable effective integration (Elghaish et al., 2023; Yang et al., 2023). The implementation of BT-enhanced DTs in public management and metaverse sectors faces transparency and proprietary right issues, respectively, but both must address big data management, policy, and legal issues (Bhushan et al., 2020; Huynh-The et al., 2023; Santana and Albareda, 2022; Yaqoob et al., 2023). Furthermore, the food industry needs to address the issues of data authenticity and the timeliness of information and data when employing BT-enhanced DTs (Shi et al., 2023; Smetana et al., 2021).

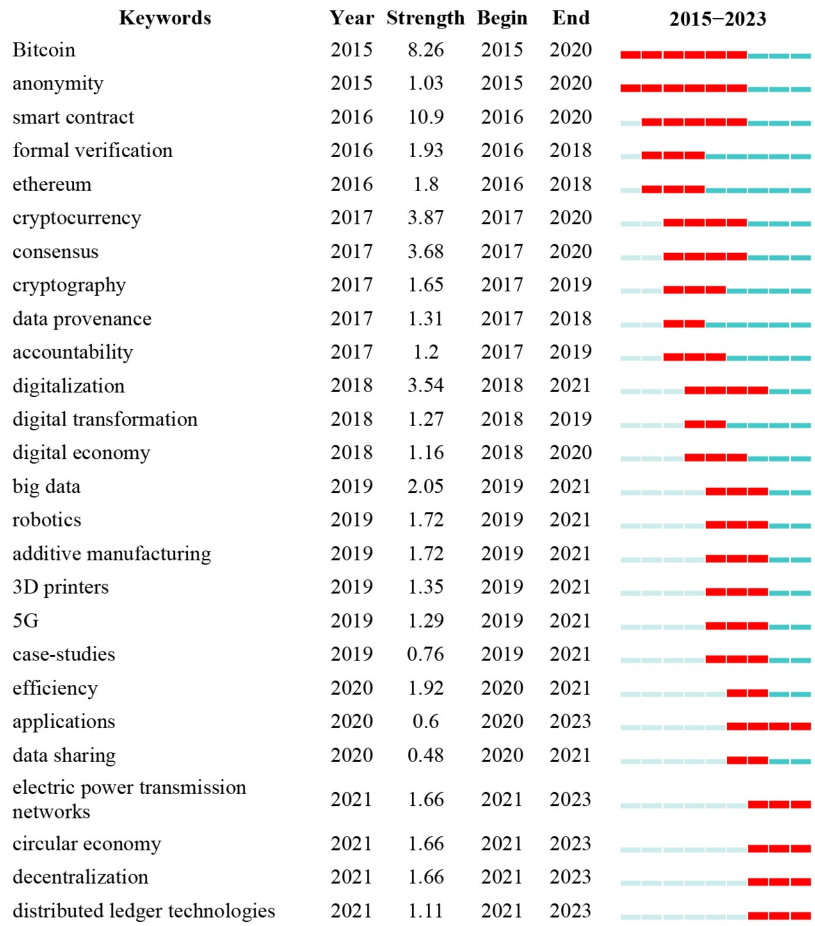
4.4 Hotspots and major subjects in the cross-sectional research of BT and DTs

RQ4: What are the hotspots and major subjects in the cross-sectional research on BT and DTs?

The analysis of burst keywords unveils a changing paradigm in the cross-sectional research of BT and DTs, as depicted in Fig. 4. Between 2015 and 2020, the primary focus, as indicated by keywords such as "Bitcoin," "anonymity," and "smart contract," was predominantly on the utilization of BT. The subsequent shift in research, spanning from 2017 to 2020, centered more on aspects of digital transformation, highlighted by terms such as "digitalization," "big data," "5G," and "3D printers." The latest trend in citation bursts, extending from 2021 to 2023, includes terms like "electric power transmission networks," "circular economy," "decentralization," and "distributed ledger technologies." These recent keywords reflect a new research direction toward developing more intelligent and sustainable BT-enhanced digital transformations.

Figure 5 organizes keyword clusters in descending order of keyword frequency, analyzed through the Likelihood test (Chen, 2016). The clusters are labeled as follows: "0# augmented reality," "1# smart city," "2# smart manufacturing," "3# cybersecurity," "4# life cycle," "5# Ethereum," "6# smart grid," "7# additive manufacturing," "8# blockchain technology," and "9# digitalization." Further insights are provided by Fig. 6, which details the timelines of these burst keywords. The cluster "0# augmented reality" ranks highest in keyword clustering, including related terms such as "virtual augmented," "metaverse," and "architectural design." Notably, "2# smart manufacturing" stands out for its significant burst, marked by the prominent presence of "digital twin," along with "artificial intelligence," "machine learning," "data analytics," and "cyber-physical system." These focal points underscore the critical role of data intelligence and DTs in this research area.

Additionally, the analysis of the keyword cluster "8# blockchain technology" indicates recent bursts of keywords related to supply chains and peer-to-peer networks, suggesting emerging areas for the application of blockchain technology in digital transformations. The keyword cluster "#6 smart grid" demonstrates the most current burst, predominantly in 2022, highlighting its ongoing relevance and diverse applications in areas such as network security and project management integration. The time-zone map of keyword bursts (Fig. 7) shows that early bursts in 2015 and 2016 were centered around blockchain and its derivatives, such as Bitcoin and Ethereum. Between 2017 and 2019, bursts involved DTs, IoT, Industry 4.0, and digital transformation. Since 2020, keywords like "metaverse," "machine learning," and "virtual reality" have gained prominence, suggesting an emerging interest in integrating the metaverse with



Keywords	Year	Strength	Begin	End	2015−2023
Bitcoin	2015	8.26	2015	2020	
anonymity	2015	1.03	2015	2020	
smart contract	2016	10.9	2016	2020	
formal verification	2016	1.93	2016	2018	
ethereum	2016	1.8	2016	2018	
cryptocurrency	2017	3.87	2017	2020	
consensus	2017	3.68	2017	2020	
cryptography	2017	1.65	2017	2019	
data provenance	2017	1.31	2017	2018	
accountability	2017	1.2	2017	2019	
digitalization	2018	3.54	2018	2021	
digital transformation	2018	1.27	2018	2019	
digital economy	2018	1.16	2018	2020	
big data	2019	2.05	2019	2021	
robotics	2019	1.72	2019	2021	
additive manufacturing	2019	1.72	2019	2021	
3D printers	2019	1.35	2019	2021	
5G	2019	1.29	2019	2021	
case-studies	2019	0.76	2019	2021	
efficiency	2020	1.92	2020	2021	
applications	2020	0.6	2020	2023	
data sharing	2020	0.48	2020	2021	
electric power transmission networks	2021	1.66	2021	2023	
circular economy	2021	1.66	2021	2023	
decentralization	2021	1.66	2021	2023	
distributed ledger technologies	2021	1.11	2021	2023	

Fig. 4 Strongest citation bursts of keywords.

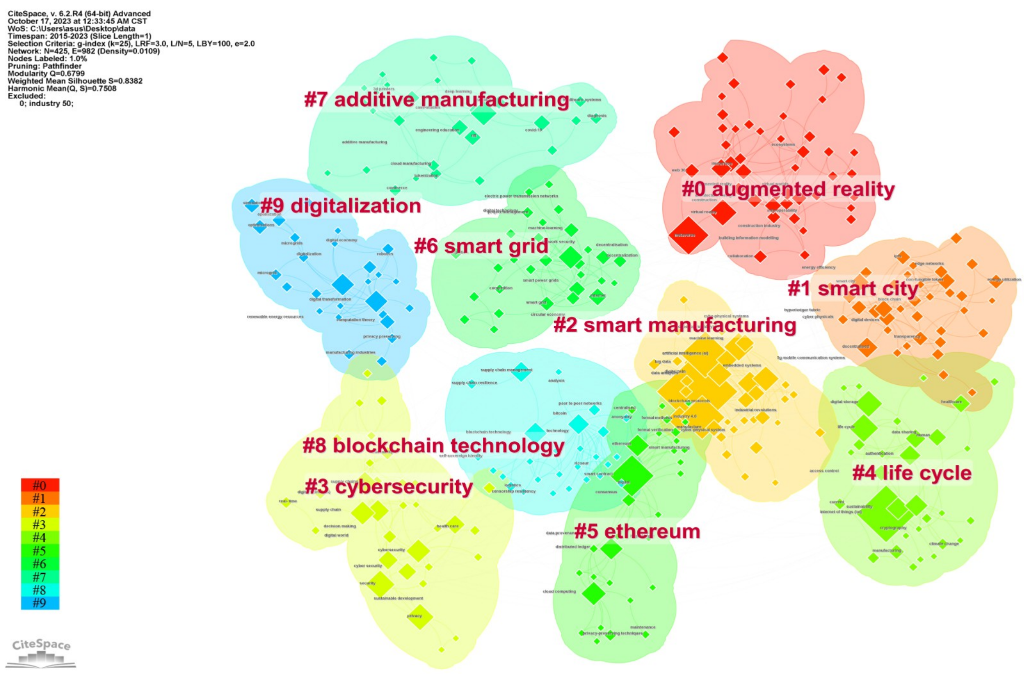


Fig. 5 Keyword clusters.

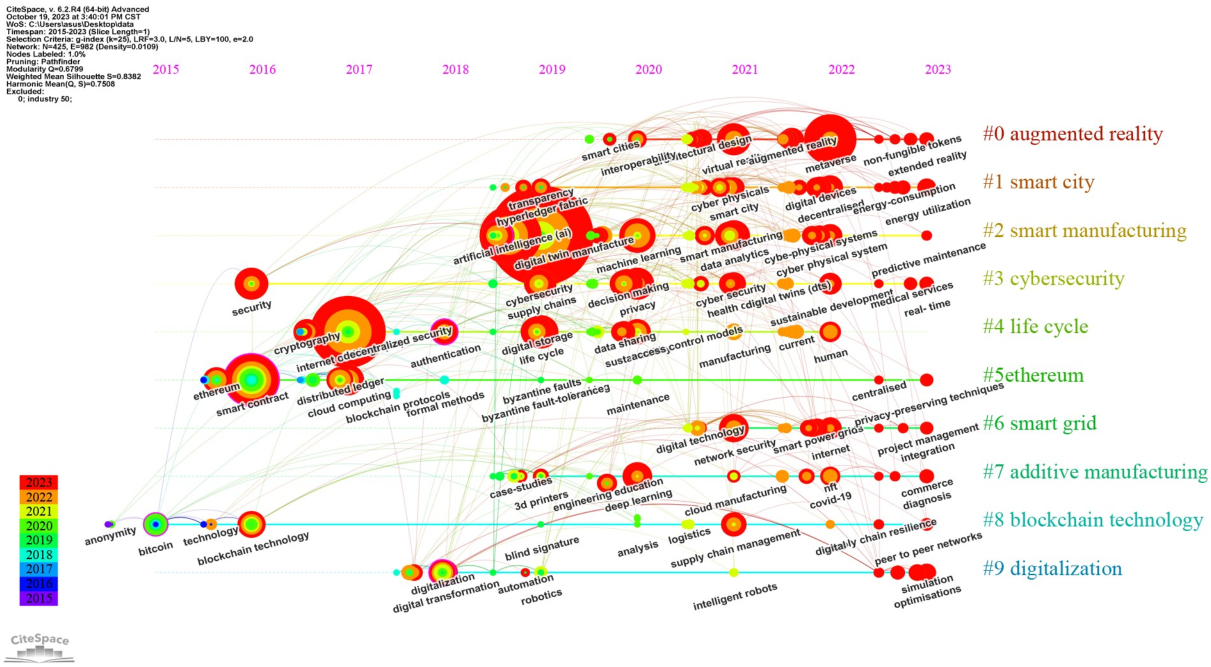


Fig. 6 Timelines of keyword bursts.

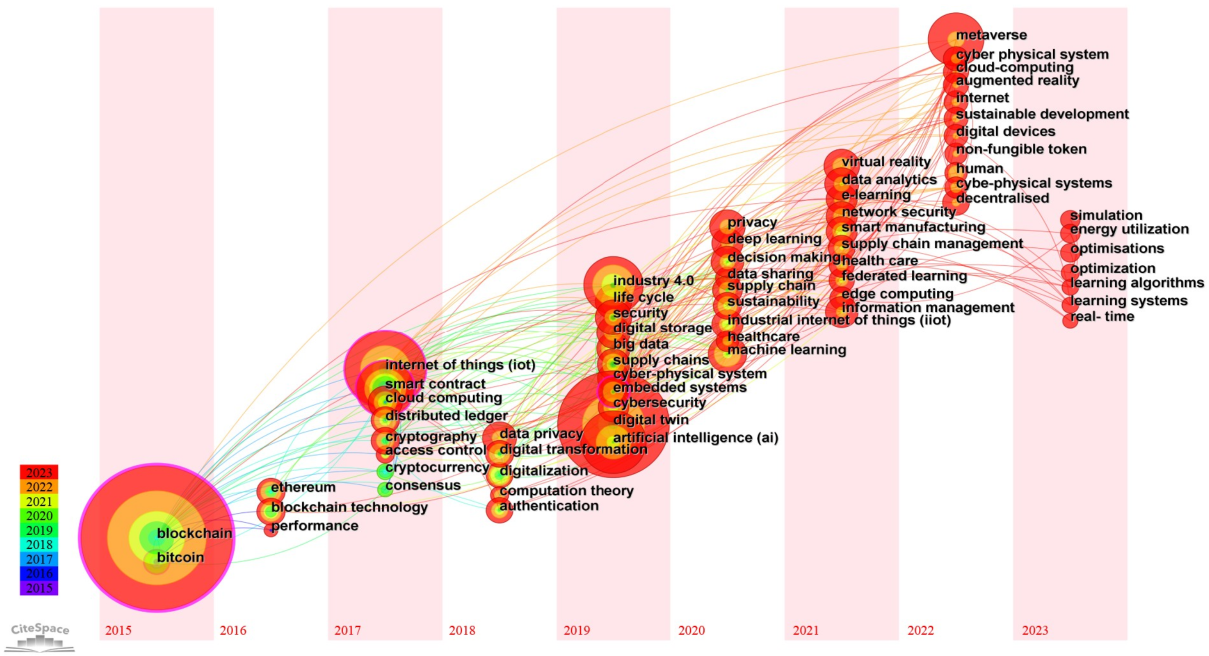


Fig. 7 Time-zone map of keywords.

BT-enhanced DTs, with a focus on human-oriented and sustainable development principles in the evolution of the metaverse.

4.5 Citation bursts and relations of the focused studies

RQ5: What are the citation relations of studies regarding the strength and timelines of the citation bursts, and how do they impact the development trend of the research?

The analysis of citation bursts provides valuable insights into the evolution of cross-sectional research involving BT and DTs. Created using CiteSpace, Fig. 8 displays the most influential references with the strongest citation bursts in the research area. An examination of these top references reveals a span from 2009 to 2020, with their citation bursts extending from 2017 to 2023.

References	Year	Strength	Begin	End	2017−2023
Nakamoto Satoshi, 2009, BITCOIN PEER TO PEER, V0, P0	2009	3.63	2017	2020	
Christidis K, 2016, IEEE ACCESS, V4, P2292, DOI 10.1109/ACCESS.2016.2566339, DOI	2016	3.25	**2019**	2020	
Tao F, 2018, INT J ADV MANUF TECH, V94, P3563, DOI 10.1007/s00170-017-0233-1, DOI	2018	2.55	**2019**	2020	
Androulaki E, 2018, EUROSYS 18 ... NTH EUROSYS CONFERENCE, V0, P0, DOI	2018	2.4	**2019**	2020	
Kennedy ZC, 2017, J MATER CHEM C, V5, P9570, DOI 10.1039/c7tc03348f, DOI	2017	2.34	**2019**	2020	
Swan M, 2015, BLOCKCHAIN BLUEPRINT, V0, P0	2015	2.34	**2019**	2020	
Abeyratne Saveen A, 2016, BLOCKCHAIN READY MAN, V5, P1, DOI 10.15623/IJRET.2016.0509001, DOI	2016	2.9	**2019**	2021	
Fernández-Caramés TM, 2018, IEEE ACCESS, V6, P32979, DOI 10.1109/ACCESS.2018.2842685, DOI	2018	1.66	**2019**	2021	
Ahram T, 2017, 2017 IEEE TECHN ...... ONFERENCE (TEMSCON), V0, PP137, DOI	2017	1.66	**2019**	2021	
Zheng ZB, 2017, IEEE INT CONGR BIG, V0, PP557, DOI 10.1109/BigDataCongress.2017.85, DOI	2017	1.19	**2019**	2023	
Lee J, 2019, MANUF LETT, V20, P34, DOI 10.1016/j.mfglet.2019.05.003, DOI	2019	5.31	**2020**	2021	
Zhong RY, 2017, ENGINEERING-PRC, V3, P616, DOI 10.1016/J.ENG.2017.05.015, DOI	2017	3.53	**2020**	2021	
Angrish A, 2018, PROCEDIA MANUF, V26, P1180, DOI 10.1016/j.promfg.2018.07.154, DOI	2018	3.09	**2020**	2021	
Khan MA, 2018, FUTURE GENER COMP SY, V82, P395, DOI 10.1016/j.future.2017.11.022, DOI	2018	3.09	**2020**	2021	
Westerkamp M, 2020, DIGIT COMMUN NETW, V6, P167, DOI 10.1016/j.dcan.2019.01.007, DOI	2020	3.09	**2020**	2021	
Xu X, 2012, ROBOT CIM-INT MANUF, V28, P75, DOI 10.1016/j.rcim.2011.07.002, DOI	2012	2.65	**2020**	2021	
Liu Q, 2019, INT J PROD RES, V57, P3903, DOI 10.1080/00207543.2018.1471243, DOI	2019	2.65	**2020**	2021	
Li Z, 2018, ROBOT CIM-INT MANUF, V54, P133, DOI 10.1016/j.rcim.2018.05.011, DOI	2018	2.52	**2020**	2021	

Fig. 8 Top references with strongest citation bursts in the cross-sectional research area of BT and DTs.

Specifically, most of these references exhibit significant bursts within a two to three-year period, primarily between 2019 and 2021. Notably, Nakamoto's work from 2009 manifested a strong burst from 2017 to 2020, registering a burst strength of 3.63, while Zheng et al. (2017) experienced a sustained burst from 2019 to 2023, with a burst strength of 1.19. Other notable studies, such as those by Lee et al. (2019), Zhong et al. (2017), and Christidis and Devetsikiotis (2016), recorded more pronounced burst strengths of 5.31, 3.53, and 3.25, respectively.

In the intersectional research field of BT and DTs, certain studies stand out in co-citation analysis, as depicted in Fig. 9. The work of Tao et al. (2019), which examines the state-of-the-art in DT applications, has

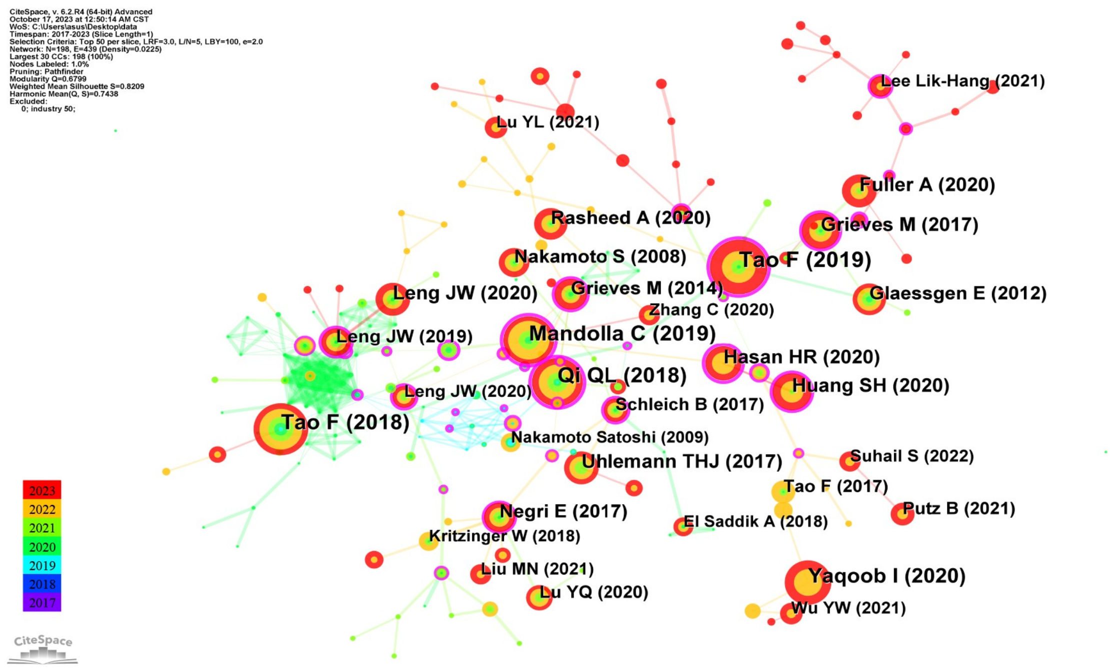


Fig. 9 Clusters of the co-citations.

received the highest number of co-citations in the field. Other significant contributors to the research landscape, such as Mandolla et al. (2019), Qi and Tao (2018), and Tao et al. (2018), also demonstrate considerable clustering of co-citations with related studies. Since 2020, studies by Yaqoob et al. (2020), Huang et al. (2020), Hasan et al. (2020), and Leng et al. (2020a) have emerged with notable clusters of co-citations in this domain. While some more recent studies show high citation counts, it is important to note that this metric favors older studies due to the cumulative nature of citation statistics. Notably, apart from Tao et al. (2019), studies with significant co-citation bursts from 2019 onwards predominantly include both BT and DTs, indicating a shift in research focus toward BT-enhanced DTs, compared to earlier works which primarily concentrated on DTs.

Figure 10 presents a detailed co-citation timeline, using bibliographic data from the most recent studies, particularly since 2017, which marks the onset of strong citation bursts as depicted in Fig. 8. The analysis outlines the 10 most prominent recent hotspots based on publication frequencies, including #0 metaverse, #1 smart healthcare, #2 Industry 4.0, #3 avatars, #4 artificial intelligence, #5 facility management, #6 federated learning, #7 hybrid business model, #8 digital ecosystem, #9 inter-organizational processes. A closer examination of the years and magnitudes of these bursts reveals that the first seven topics, #0-6, exhibit more pronounced and recent bursts compared to #7, #8, and #9. Notably, #0 metaverse stands out with the most significant bursts in the latest years, highlighting its growing importance in this area. The keyword-author timeline analysis of these contemporary studies provides valuable insights into the latest developments and emerging trends in the research field.

5 Research development, trajectory, and future directions

5.1 Further interpretation of the findings for developing BT-enhanced DTs

Figure 11 presents a development framework for BT-enhanced DTs based on keywords identified through bibliometric analysis. The framework adopts a typological approach, integrating the theory of technology diffusion policy by Park (1999) with empirical insights from the review. It outlines various layers, including supportive technologies such as the IoT, BIM, and DLT, core applications of BT and DTs, benefits and functions like cybersecurity, interoperability, and anonymity, mainstream application contexts like metaverse, smart grids, and smart cities, and overarching objectives like digitalization, automation, intelligence, sustainable development, and human-oriented design. This comprehensive framework guides the development and progression of BT-enhanced DTs, illustrating a logical trajectory from foundational elements to advanced applications. The layered structure maps the evolutionary path of BT-enhanced DTs, tracing the technology's advancement from enabling mechanisms to practical applications.

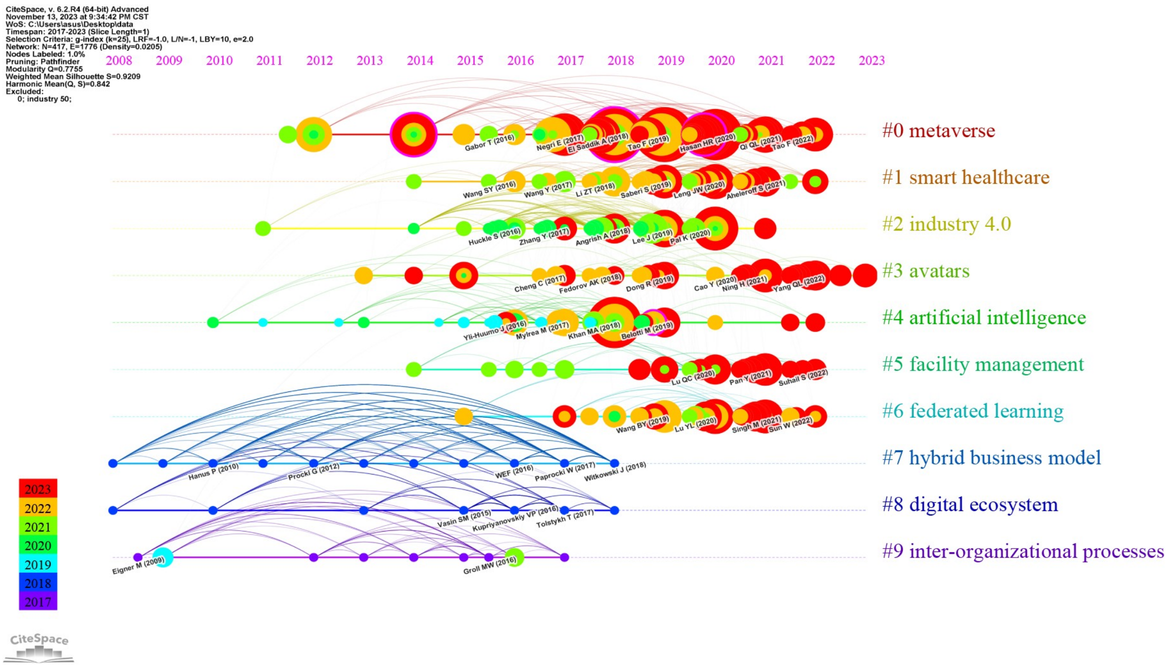


Fig. 10 Co-citation timelines of the most recent studies.

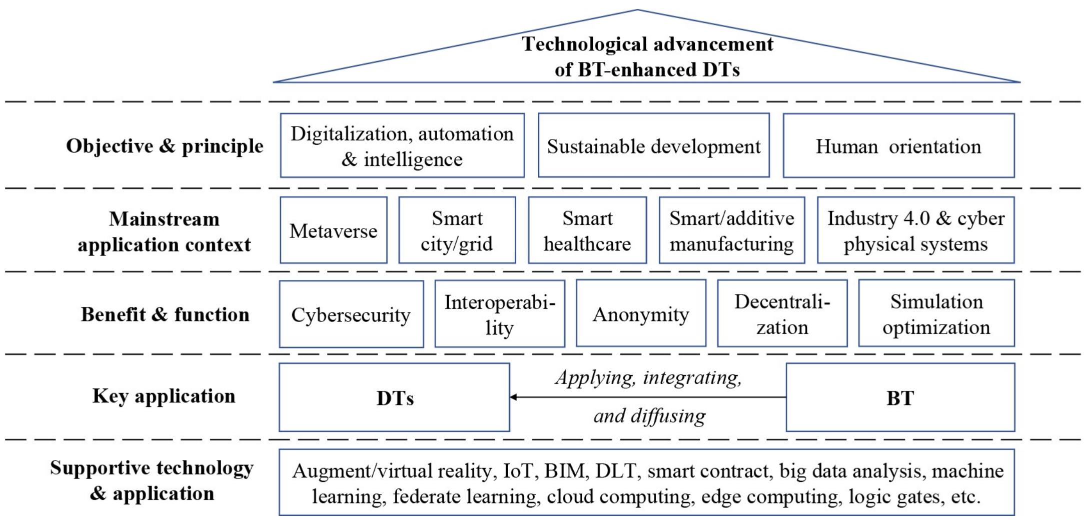


Fig. 11 A development framework of BT-enhanced DTs.

5.2 Emerging research trends in the cross-sectional research of BT and DTs

The analysis results depicted in Figs. 4–7 plays a crucial role in charting the research trajectory within the cross-sectional study of BT and DTs. The keywords burst timeline reveals a progressive shift in research focus over time. Initially, the emphasis was on developing technical solutions involving BT and DTs. This progressively transitioned to the utilization of advanced technologies, followed by industry-specific deployment and applications of these technologies. The burst analysis of citations further illuminates this transition, highlighting three primary stages in the research landscape: technology development, technology use, and technology deployment. Each stage represents a significant phase in mainstream research, tracking the journey from foundational aspects of BT and DTs to their practical and specific applications across various industries.

In analyzing the strength and timelines of pivotal studies in the field of BT and DTs, several research hotspots have emerged. These hotspots include diverse aspects, such as: 1) Frameworks and architecture of DT models based on distributed control solutions, exemplified by works like Alam and El Saddik (2017), Muralidharan et al. (2023), and Lee et al. (2019); 2) Technical solutions for integrating BT into DTs, as seen in studies by Kumar et al. (2023), Leng et al. (2019b), Mandolla et al. (2019), and Westerkamp et al. (2020); 3) BT-based solutions approaches to augment sustainability in DTs, highlighted in research by Abou El Houda and Brik (2023), Leng et al. (2020a), and Wang and Wang (2019); 4) The synergistic use of BT-enhanced DTs with other advanced technologies, with notable examples from Fragapane et al. (2022), Singh et al. (2022), and Tao et al. (2022); 5) The application of BT-enhanced DTs in decentralized automation and smart operation, as explored by Leng et al. (2023), Sahal et al. (2022), and Yan et al. (2022); 6) Industrial deployment of BT-enhanced DTs, detailed in studies like Fragapane et al. (2022), Raja Santhi and Muthuswamy (2023), and Suhail et al. (2022a); and 7) The utilization of BT-enhanced DT applications in metaverse, a growing area of interest seen in works by Yaqoob et al. (2023), Banaeian Far et al. (2023), and Yao et al. (2024).

Expanding upon the aforementioned interpretation, Fig. 12 illustrates the primary research trajectory within the cross-sectional study of BT and DTs. This trajectory is characterized by three distinct stages of research development: technology development, technology use, and technology deployment. These stages encapsulate the various research hotspots identified earlier. Of particular note is the research hotspot focusing on BT-based solutions to enhance sustainability with DTs. This area can be considered as part of the technology use stage but with a strong inclination toward technology deployment. This emphasis reflects the growing necessity to respond to environmental changes and the pressing demands of climate sustainability, thereby positioning this area as a critical intersection of practical application and future-focused development.

5.3 Research opportunities and future directions

The comprehensive literature review reveals several promising avenues for future research on the integration of BT into DTs and the advancement of BT-enhanced DTs. Specifically, there is potential for more in-depth studies on the complex integration of BT into DTs, aligned with the development framework illustrated in Fig. 11. This would involve exploring advanced methodologies and integrated applications based on this framework. Moreover, the further development of BT-enhanced DTs requires more affordable and convenient exploitation of technology and data, employing advanced approaches such as AI and big data (Hakimi et al., 2024; Hemdan et al., 2023; Liu et al., 2023a). Therefore, further exploration of technology development can focus on improving technology affordance and updating data processing methods with innovative techniques.

To break away from established path dependencies and enhance existing applications using BT-enhanced DTs, there is a valuable area of exploration. As depicted in Fig. 12, current research primarily focuses on technology deployment. However, given that BT-enhanced DT represents a novel technological approach, it is crucial to investigate the iterative development and path-dependence effects in technology use. This includes examining scenarios where BT-enhanced DTs could surpass existing information system solutions and strategies to promote their wider adoption. For example, recent studies have shown successful deployment of BT-enhanced DTs in the manufacturing industry (Gopal et al., 2023; Leng et al., 2023), while others indicate that BT-enhanced DTs

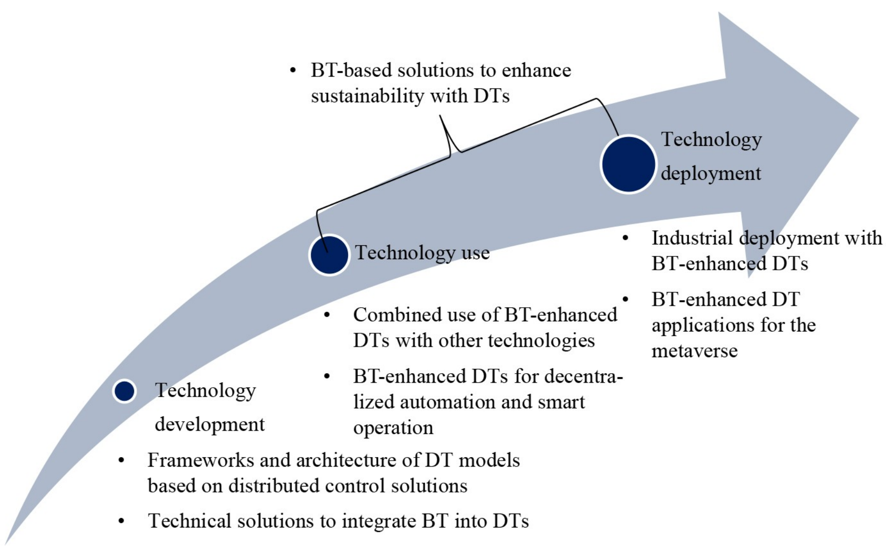


Fig. 12 The development of the cross-sectional research of BT and DTs.

remain at the technology-use level in the construction industry (e.g., Adu-Amankwa et al., 2023; Zhang et al., 2023). Further research can focus on explaining the reasons behind this phenomenon, which would significantly contribute to sector-based deployment of BT-enhanced DTs.

Additionally, future research must also address regulatory and governance challenges, aspects that have often been overlooked in technology deployment studies. The integration of BT into DTs can either simplify regulatory and governance processes due to enhanced security features, or these issues may have been underrepresented in existing research. Investigating these aspects is a critical direction for scholarly inquiry, ensuring that technological advancements align with legal and ethical frameworks, particularly in public management and healthcare domains (e.g., Hemdan et al., 2023; Manocha et al., 2023; Yaqoob et al., 2023). This approach would enhance the understanding of BT and DT integration while addressing practical implications and societal impacts. Theoretical studies are currently needed in this area as they play a crucial role in guiding the deployment of technology.

6 Contributions and implications

6.1 Theoretical contributions

This review study makes several significant theoretical contributions to the field of BT and DTs. First, it successfully identifies and delineates the current landscape in cross-sectional research of BT and DTs. By constructing a comprehensive framework of existing research, this study effectively profiles the entire research area. This approach not only deepens the understanding of the dynamics behind the integration of BT in DTs but also sheds light on the nuances of implementing BT-enhanced DTs. Furthermore, this study systematically classifies the existing literature and synthesizes research findings to clarify the functional role of BT in enhancing DTs. This includes a thorough analysis of how various features and technologies within BT contribute to the development and efficiency of DTs, ultimately enriching the existing body of knowledge. Additionally, this study utilizes bibliometric evidence to underscore the prevailing research trends, hotspots, and focused subjects within the field. This meticulous analysis lays out the trajectories of research development, pinpointing the most contemporary directions and areas of interest. Through this process, this study not only augments the collective understanding of BT and DTs research but also establishes a robust theoretical foundation for future explorations in the domain of BT-enhanced DTs. This holistic view not only informs current academic discourse but also guides future research in this rapidly evolving field.

6.2 Practical implications

The insights gleaned from this study offer several practical implications, particularly for practitioners in the field of BT and DTs. First, the study elucidates how BT can effectively enhance DTs, which is crucial for those seeking to advance the use of BT within DTs or to re-engineer BT-enhanced DT systems. This understanding is especially valuable for practitioners contemplating the integration of BT to augment DT functionalities. Secondly, the study identifies and clarifies various challenges associated with integrating BT into DTs. This clarity provides practitioners with informed directions for improvement, enabling them to make more strategic decisions regarding the use of BT in DTs and enhancing the implementation of BT-enhanced DT systems. Thirdly, the study presents a comprehensive framework for developing applications of BT-enhanced DTs. This framework is not only crucial for the advancement of CPSs but also plays a pivotal role in inspiring developments within the metaverse. By providing a structured approach to application development, this framework equips practitioners with a valuable tool to navigate the complexities of integrating BT in DTs and harness the full potential of these technologies in various practical scenarios.

7 Conclusions

This study presents a comprehensive review of the research landscape on BT and DTs. It effectively assesses the current status and development trends in this field. By addressing the RQs proposed, several important insights have been uncovered.

- Regarding RQ1, Fig. 2 demonstrates a significant increase in the volume of cross-sectional research on BT and DTs. The frequency of publications has notably doubled in 2019 and 2022 compared to 2017, indicating substantial growth beyond the initial emerging stage of this research domain.
- To address RQ2 and RQ3, the study provides a detailed analysis of how BT impacts DTs, as well as the challenges faced in integrating BT within DTs. These are thoroughly discussed in Sections 4.2 and 4.3, respectively.
- For RQ4, Figs. 5–7 illustrate the primary research areas and major subjects in cross-sectional research on BT and DTs. These findings identify the key areas of focus within the field.
- In response to RQ5, the study reveals a tripartite developmental framework for DTs incorporating BT. This framework consists of technology development, technology use, and technology deployment. This

progression is supported by the burst analysis of keywords and co-citations, as depicted in Fig. 12. The bibliometric evidence gathered suggests that the integration of BT into DTs is moving toward more intelligent, sustainable, and human-oriented technological applications.

Overall, these findings provide a comprehensive view of the current research landscape at the intersection of BT and DTs. They also establish a solid foundation for further research in BT-enhanced DTs.

This review study is crucial in identifying key technology management issues related to the integration of BT into DT and in defining clear research pathways for the advancement of BT-enhanced DT applications. It effectively maps out the cross-sectional field of BT and DTs, highlighting its hotspots, focused subjects, and development trends. This comprehensive portrayal enhances the understanding of the current knowledge base in this domain and establishes a solid theoretical foundation for further exploration into BT-enhanced DTs. Furthermore, the study provides a clear explanation of how BT functions within the context of DTs and pinpoints specific challenges associated with the integration of BT into DTs, as well as the implementation of BT-enhanced DTs. This insight is crucial for advancing the application and utilization of BT in DTs, and for refining the deployment of BT-enhanced DT systems. One prominent area for future research is the issue of path-dependence in technology deployment, requiring a deeper exploration of how established practices and technologies influence the adoption of new BT-DT integration. Additionally, examining the regulatory and governance frameworks that support the integration of BT into DTs emerges as another significant avenue for research. These areas represent promising directions for accommodating future studies within the cross-sectional field of BT and DTs, offering opportunities to address critical challenges and drive innovation in this evolving technological landscape.

Although this study offers valuable insights, it does have limitations. One inherent challenge in conducting review studies is defining the scope of the review. In this case, the focus was placed on critical aspects identified through the investigation process. However, this approach may have inadvertently overlooked a small proportion of related studies that could provide additional perspectives or nuances. Additionally, while software analysis provides a robust tool for handling large data sets, it may not capture certain nuanced or unidentified issues. To mitigate this limitation, the study employed manual examination as a complementary method. Nevertheless, due to the extensive volume of literature reviewed, it was challenging to distinguish between theoretical and empirical studies comprehensively. Such differentiation often requires a more qualitative approach, which could be a focal point for future research endeavors. These limitations highlight areas for potential improvement and refinement in future studies. Future researchers could explore a more nuanced and qualitative analysis to capture a wider range of studies, including those that might have been omitted in this review. Furthermore, a more detailed classification of the literature into theoretical and empirical categories could provide deeper insights and a more granular understanding of the field.

Competing Interests The authors declare that they have no competing interests.

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