Evolutionary Intelligence (2024) 17:1257–1278
https://doi.org/10.1007/s12065-023-00872-w

REVIEW ARTICLE

# From assistive technology to the backbone: the impact of blockchain in manufacturing

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Received: 12 February 2023 / Revised: 30 July 2023 / Accepted: 6 August 2023 / Published online: 29 August 2023


## Abstract
Blockchain refers to a collection of digitally connected applications originated to enable secure financial transactions but soon has evolved as a reliable tool for secure data management as well as the foundation for smart and sustainable manufacturing. This article tracks the evolution of blockchain technology for smart manufacturing using data mining approaches and tracks the critical developments in the field. We show that blockchain technology in manufacturing is still in its infancy and is expected to lay foundations for the development of the next levels of industrial revolution. We track the inter and intra-disciplinarity of the technology and knowledge diffusion between its various domains by clustering the technology into fifty-five subdomains. The developments in each of these subdomains are discussed in addition to tracking the knowledge gaps and future research initiatives to further develop the technology. Based on the knowledge gained from these analyses, a roadmap for intelligent blockchain technology for sustainable manufacturing is proposed. The conceptual evolution model presented herewith could be the key for the ultimate symbiotic phase in which material sources to end-users are linked by the internet of everything enabled by intelligent blockchain and human-cobot cohabitation.

**Keywords** Blockchain technology · Manufacturing · Sustainability · Fourth industrial revolution · Circular economy · Fake detection · Knowledge diffusion · Product reliability · Bionics · Machine autonomy · Cobot

## 1 Introduction

Defining sustainability as the new normal by most of the countries brought in advanced concepts such as circular economy [1–3], zero-carbon technologies [4, 5], sustainable materials and technology [6], data science [7, 8], blockchain technology [9], etc. in diverse areas of life. Among these, blockchain technology (BT) plays a vital role in contributing to environmentally sustainable development goals (SDGs) from various perspectives, such as facilitating the realisation of a sustainable supply chain, improving energy efficiency, and promoting the development of reliable and secure smart cities. BT is viewed as a unique system for diverse digitally connected applications [10]. A blockchain stores data in blocks, unlike traditional databases. When filled, blocks are closed and connected to the preceding block, producing the blockchain. All new information added after a block is added is compiled into a new block and uploaded to the chain. The links between blocks and their content are protected by cryptography, and hence the transactions cannot be forged. Thus the data in the form of blockchain distributed across a network can be trusted without the intervention of a central authority to monitor [11–13]. This concept of BT is illustrated in Fig. 1. The BT allows the transfer and process of data securely through specialised software platforms to manage the transaction of each data block carrying a title with a timestamp, a link to the preceding block, and transaction data [14, 15]. Additionally, each

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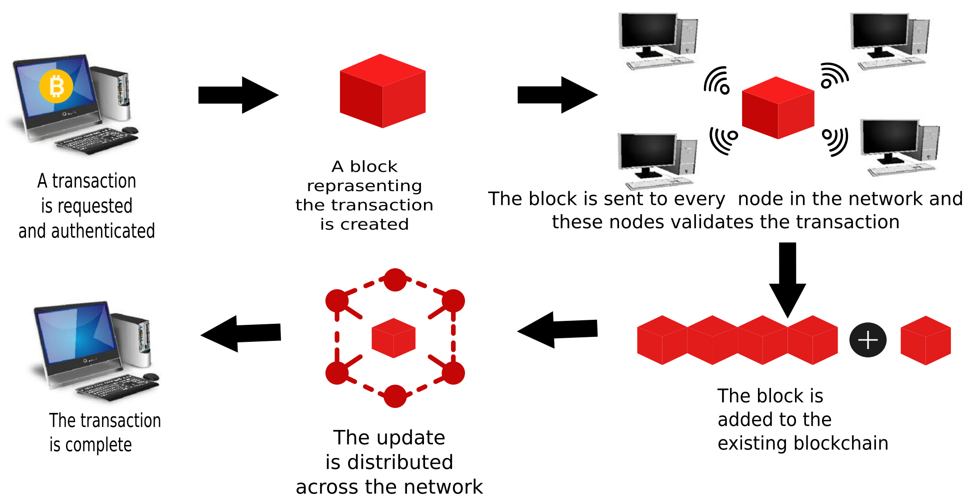



**Fig. 1** The schematic diagram of blockchain, which is a shared, immutable digital ledger distributed across a network, eliminating the need for a central authority to verify each transaction. A new record called a block, is added to the existing chain of records after validation by the majority of the nodes in the network. Each block contains a unique cryptographic identifier known as a hash, a timestamp and the hash of the previous block. Therefore, tampering with a recorded block necessitates altering all subsequent blocks, which are computationally prohibitive and almost impossible, to make it more secure

block generates a content-based hashtag and refers to the succeeding block's title, making it hard to manipulate any block as it leads to inconsistencies, as shown in Fig. 1 [16, 17]. The BT has gained wide acceptance as a robust and reliable technology for secured interactions within multiple decentralised devices [18, 19]. Due to its efficiency, cost reduction, privacy, confidentiality-integrity-accessibility, security, decentralisation, and information tracking features, blockchain applications are expected to make unprecedented progress closely related to the domains of education, banking, e-commerce, food technology & shipping, healthcare, voting, crypto-currency, Industrial IoT and supply chains [20–22]. Consequently, blockchain is currently evolving as a critical technology providing secure, cost-effective, and decentralised solutions while improving the efficiency of other technologies such as artificial intelligence [23], 5 G [24], and Internet of Things (IoT) [22, 25].

Bitcoin is the first and foremost application of blockchain technology: an anonymous person or group called Satoshi Nakamoto [26] deployed the concept of BT in 2008 to create encrypted currency or bitcoins, which has proved its efficiency in making transactions without double spending [27]. Later, the potential of BT in managing and utilising connected data has been identified in many domains [22, 28]. The global market for blockchain technology is expected to rise at a CAGR of 85.9% from 2022 to 2030, from USD 5.92 billion in the year 2021 to USD 1,431.54 billion by the year 2030 [29]. According to the assessments of opportunities of BT at the use-case level in 2018 by McKinsey, the manufacturing sector lags behind financial service, technology, media and telecom [30].

Sustainable manufacturing refers to producing manufactured products using energy and resource-efficient processes that are also ecologically benign. Additionally, sustainable manufacturing enhances worker, community, and product safety. Sustainability is becoming an increasingly significant aim in the strategy and operations of many businesses in order to boost their growth and worldwide competitiveness. As a result, many well-known companies in a wide range of industries are joining the *green* movement, which is no longer limited to a narrow niche. Corporations want sustainability for several reasons, such as reducing expenses and waste to boost efficiency, firm's long-term health and profitability to regulatory possibilities and restrictions and boost competitiveness. Industries, through the 4th Industrial Revolution paradigm (IR4.0), target their operation without any human interventions by creating, moving, securing, and handling data to enable smart manufacturing [31, 32]. For this purpose, various technologies have been incorporated into the industrial production process. The large volume of data created in industries also supports the paradigm shift, enabling any organisation to make data-driven decisions. The projected characteristic of Industry 5.0 is the environment of human-robot collaboration, progressing to total machine interdependence in Industry 6.0. Due to changing market requirements and advancing technologies, the traditional manufacturing processes and systems are currently being adapted into the new smart manufacturing protocols [33]. In a smart factory, cyber-physical systems (CPS) in production lines become more and more integrated and inter-connected [34, 35]. The evolving technologies in blockchain can reduce information asymmetry and inconsistencies between business partners, thus improving governance in a complex system [36]. The BT ensure data integrity and prevent single-point failure and malfunction [37], thereby taking a lead role in supporting the smart manufacturing protocols.

The BT is still in the rapidly evolving stage of development; a simple search in the Scopus database using the keyword "blockchain" on 27 June 2022 retrieved nearly 32,146 research articles. Over 90% of these articles have been published since 2017, thereby emphasising the significant attention of the academic research on BT. Consequently, many research articles, surveys and reviews discussing different aspects of BT are published [38–42]. For example, Zheng et al. [38] analysed the challenges and opportunities in BT; Andoni et al. [39] reviewed applications of BT in the energy sector; Li et al. [41] surveyed the security aspects of BT systems; and Wang et al. [40] on BT for IoT. In a recent study, Rožman et al. [43] examined the influence of blockchain scalability limitations on the performance and user behaviour within blockchain-based shared manufacturing systems, utilising an experimental approach. Recently, Guo et al. [44] examined how blockchain technology is integrated into smart manufacturing. The study offers valuable insights into the framework, challenges, and potential research directions related to this integration. Mourtzis et al. [45] examined the implications of blockchain technology in overcoming the emerging cybersecurity challenges for safe and intelligent manufacturing in Industry 5.0. However, to the best of our knowledge, progress in BT applications in manufacturing or the smart industry needs to be adequately reviewed in a comprehensive manner. Citation network analysis (CNA) provides an insightful, systematic approach to understanding the dynamics of research and development in complex, interdisciplinary fields like blockchain's role in manufacturing [46–50]. Despite abundant reviews, this field's interconnected and multi-disciplinary nature can limit comprehensive understanding. The citation network enables an exploration of the key historical pathways and topics of research. Traditional methods may restrict focus, data sets, or time spans, leading to potential blind spots. With the proliferation of research articles, CNA leverages efficient computing techniques to process voluminous bibliometric information, offering insights into early innovation indicators.

Furthermore, CNA provides a holistic understanding of the knowledge structure, identifying sub-domains and their thematic connections. It also maps the evolution of research trends and foresees future directions, thereby providing a valuable tool for strategic planning and policy-making. Hence this study aims (i) To trace the evolution and emerging research trends of BT in manufacturing, and to elucidate an overview of research trends in BT applications in manufacturing (ii) To map the scientific profile and analyse the diffusion of knowledge, and (iii) To provide a topic evolution model to roadmap future research trends of BT applications and conceptual evolution model in the next generation industry employing the computational tools of CNA. Some of the specific research questions we tried to address in this paper are as follows. (i) Which institutions and countries are top contributors? (ii) What are the milestone papers and their contributions to the evolution of the domain? (iii) What is the chronological evolution of the active research areas? (iv) What are the emerging themes? (v) What are major subdomains, and how do they interrelate? (vi) What future research will lead the roadmap ahead?

The main challenge is to analyse the research corpus of a multi-disciplinary area involving diverse technologies. Using bibliographic data, we employ citation network analysis (CNA) to portray the knowledge structure and emerging trends in BT's application in the smart industry. Citations provide a network of information that traces the growth of a field from its earliest days to the most recent frontiers of scientific inquiry. This method has demonstrated its efficacy as a computer-aided technology forecasting tool and an alternative to an expert-based approach [48, 49]. A directed network, known as a citation network, can be constructed with articles as nodes and citations as edges. These edges enable the exploration of leading routes of information flow in the progression of research topics, adhering to the principles of complex network theory. Over the years, citation network analysis (CNA) has emerged as a systematic and scientifically validated approach for analysing research articles in a particular field to identify research fronts, evolving techniques, and future trends. A complex network formed by citations represents a wealth of information about the evolution of the area under study and its research fronts. Drawing upon social network analysis (SNA) tools, CNA has evolved as a computer-based technology forecasting tool, offering a viable alternative to expert-based approaches [51–54].

The structure of this paper is as follows. The following section provides the main path analysis tracing the evolution of BT research in manufacturing. The third section deals with science mapping and knowledge diffusion, which is followed by analysis of subdomains and their coupling (Sect. 4), the roadmap ahead (Sect. 5) and conclusions and key messages (Sect. 6).

## 2 Evolution BT research in manufacturing

An algorithmic literature review method is quickly developing as a viable alternative to expert-based analysis as the body of scientific literature expands exponentially and becomes more interdisciplinary. Manufacturing literature is no exception since it integrates a wide range of technologies. The citation network analysis has become a prominent tool in this approach. A comprehensive examination of BT research and development in smart manufacturing was carried out using CNA to examine the milestone developments in knowledge creation. To follow the expansion of the knowledge domain in BT, the Web of Science (WoS) core collection, because of its broad coverage of high-quality journals of science, engineering and technology, was queried for published works on topics *blockchain* and *manufacturing*, excluding review articles, editorial material, correction, retraction, book chapters, without language or period restrictions. The retrieved data was then utilised to build the citation network using the Science of Science (Sci$^2$) tool [55]. The nodes in the citation network represent articles, and an arrow connecting between two nodes represents the citation. The retrieved articles form a citation network with 17058 nodes representing the articles in the retrieved data and the references therein and 19231 directed edges representing citations. The citation network was subsequently utilised to build the main path of evolution.

We used citation analysis to learn about academic research dynamics on blockchain applications in manufacturing from publications, journals, and author, institution, and country collaboration. Figure 2 summarises the exploratory analysis showing top contributors. Because the themes treated are novel and globally relevant, the top contributors to the most influential papers are the USA, China, and Australia, as shown in Fig. 2. The South China University of Technology and the University of Brussels have greatly aided this topic. Thus, these institutions are vital in creating and distributing blockchain knowledge in manufacturing. The most referenced journal was the International Journal of Production Study, followed by the International Journal of Distributed Sensor Network. The top-cited article by Xu et al. [56] highlights rapid industrialisation and new manufacturing technologies. Corporations have already begun implementing blockchain concepts into their production processes because of its scalability, security, openness, accountability, and capacity to time-stamp sensor data. According to Rahmanzadeh et al. [57], blockchain technology integrated platform for small and medium manufacturing enterprises to create a trustable network that solves big data security problems with product development and customisation. They emphasised that a new method based on blockchain technology gives tools to protect intellectual property rights in manufacturing enterprises. Di Li from the South China University of Technology, Guangzhou, China, is the top-cited researcher in this domain with more than 150 articles and eight patents, followed by her collaborators Wan, Jiafu, Wang, Shiyong and Zhang, Chunhua. The countries and top institutions in terms of citations received, as highlighted in Fig. 2, provide a quick overview of how research and development in this domain is geographically distributed.

## 2.1 The main path of evolution

The main path is a subgraph of the acyclic-directed citation network connecting the milestone papers in the evolutionary path. It is a generally established method in the literature to

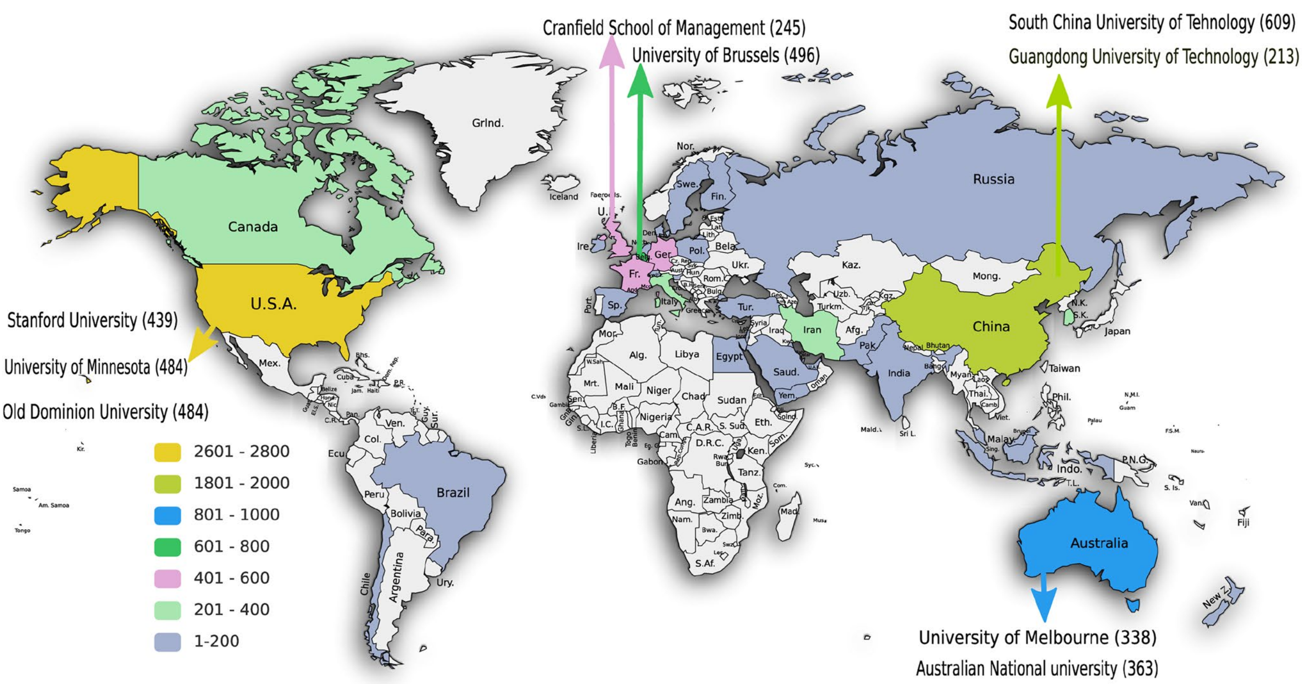



**Fig. 2** The summary of the exploratory analysis of research literature on blockchain technology in manufacturing showing country and institution-wise the top contributors. The numbers in parentheses show the number of citations

trace knowledge evolution in an area [58–61]. The global main path was retrieved and examined to show the evolution of research themes and focus shifts using PAJEK [62].

An acyclic-directed network's main path is the most important nodes' linkages. Weight-directed links between nodes to discover a citation network's main path. Hummon and Dereian (1989) suggested Search Path Link Count (SPLC) to estimate link weights. A directed link's SPLC counts all search paths in the acyclic network from its tail node to ancestor nodes [60, 63]. A connection's SPLC includes all network search paths. A citation network develops its main path by adding high-weight links from a source node to a sink node. Each major path connection spreads knowledge to subsequent publications and is used to track scientific evolution [58, 59, 61]. Global principal pathways are most traversed. The global main path is the link with the highest traversal count from all sources.

The main path, showing the milestone papers in the evolutionary trajectory of the domain, shown in Fig. 3, begins with an article by Kennedy et al. [64] on fighting counterfeits in the worldwide supply chain for additive manufacturing. The popularity of additive manufacturing is significant due to its open-source printing processes, lower cost and capital hurdles than traditional manufacturing. Still, it led to the situation wherein manufacturers and end-users need to confirm the authenticity and quality of individual parts as production becomes democratised. To combat counterfeiting, Kennedy et al. [64] proposed a method of embedding nanoparticles in 3D-printed objects and non-destructively measuring a chemical signature profile. Chemical signature data is secured, disseminated, and time-stamped in a blockchain ledger. They demonstrated the efficacy of the method by formulating and transforming lanthanide-aspartic acid nanoscale coordination polymers (Ln3+-Asp NCs)/poly(lactic) acid (PLA) composites into a filament feedstock for fused deposition modelling (FDM) 3D printing. The part-specific signature data is time-stamped in the blockchain. Thus, it can be observed that eliminating fake products was a key driver behind the introduction of blockchain into manufacturing. The articles authored by Li [65] and Choi et al. [66] are two significant studies published before their work and explored ways to prevent counterfeits. Choi et al. [66] developed a data processing and synchronisation algorithm for establishing initial electronic product pedigrees. These advancements in detecting counterfeit products represent the initial phase of BT deployment in manufacturing.

The second phase was about BT and the Industrial Internet of Things (IIoT) in social manufacturing. A conceptual architecture for product development information systems based on blockchain technology was proposed by Papakostas et al. [22], who presented a test scenario of product development using additive manufacturing technologies. Then Leng et al. [67] presented the Makerchain decentralised blockchain-based model to handle the cyber-credit of customised product needs in the new social manufacturing paradigm. This technology automates maker transactions

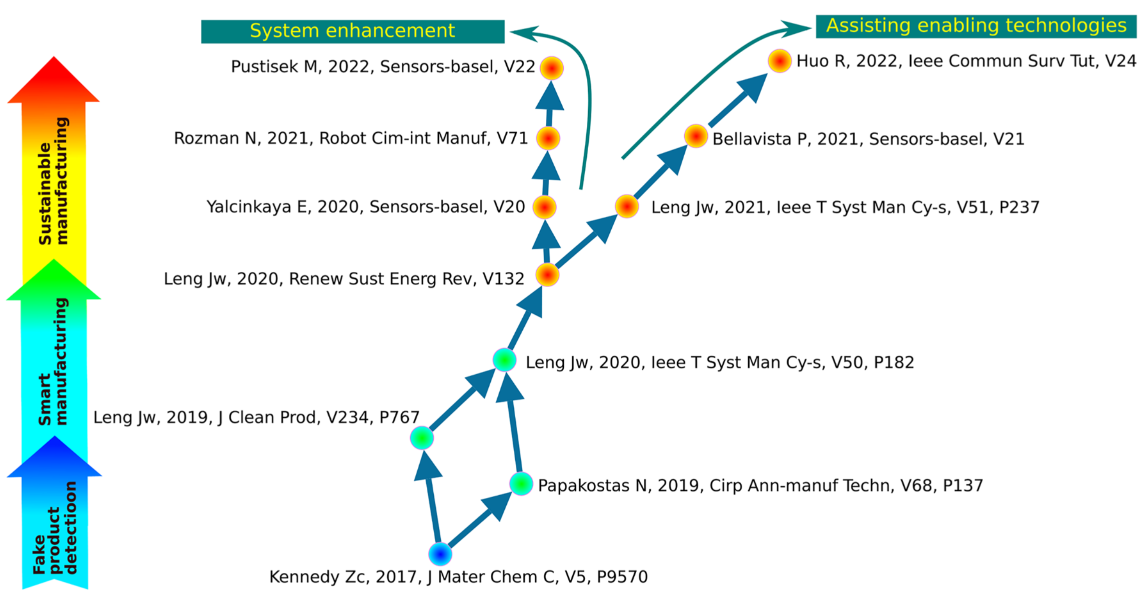



**Fig. 3** The global main path of evolution of blockchain technology in manufacturing. The nodes in the main path show the milestone papers in the evolution of BT in manufacturing. Along the main path, three stages of development are observable: the first stage focuses on counterfeit product identification, the second stage focuses on smart manufacturing, and the third stage focuses on sustainable manufacturing. The third phase saw two distinct streams of activity: attempts to strengthen the system as a whole and BT's involvement in assisting with enabler technologies

and verifies product lifecycle by a third party. It proposes a blockchain-based digital twin-sharing platform for software copyright protection and distributed heterogeneous resource integration. In addition, the digital twins can be used for open smart manufacturing system commissioning [68] and resource allocation in shared production [69]. For consistency between planning and execution in personalisation systems, Leng et al. [70] suggested an intelligence system named *ManuChain*. This proposed blockchain-based IoT system facilitated decentralisation and improved factory planning. ManuChain II is a concept that combines advanced technologies such as blockchain, smart contracts, and decentralised autonomous manufacturing to create a digital twin of the manufacturing process. This digital twin can monitor and control the physical manufacturing process, enabling greater resilience and adaptability in Industry 5.0. The core of the ManuChain II approach is using a blockchain smart contract system that acts as the digital twin of the manufacturing process. This system is designed to replicate the physical manufacturing process in a digital environment, enabling real-time monitoring and control of the manufacturing process. The ManuChain II approach is a promising strategy for creating a resilient and adaptable manufacturing process in Industry 5.0. [71].

The third phase of development is characterised by the application of BT to product lifecycle management in sustainable manufacturing [72]. This phase also witnessed the growth of a blockchain reference design for automating enterprise and control system interfaces. Leng et al. [73] highlighted eight significant cybersecurity concerns in manufacturing systems and recommended ways to address them using BT. As seen from the Fig. 3, development in the third phase is divided into two branches: the left branch handles the manufacturing system as a whole. In contrast, the right branch addresses difficulties linked to the interconnectivity of various enabling technologies.

The fourth industrial revolution (Industry 4.0) will require blockchain technology. It is often seen as a big boost to enterprise digitalisation, resulting in substantial blockchain investments. There is. However, no single blockchain technology and the solutions do not communicate with one another. Due to the decentralised nature of Industry 4.0, a single blockchain solution cannot be imposed. Each organisation has its own blockchain, which must communicate with one another seamlessly. Despite numerous proposed solutions, the issue of blockchain interoperability persists. Bellavista et al. [74] recently examined the idea of providing interoperability between blockchains managed by distinct organisations.

Industry 4.0 is a huge opportunity for global productivity innovation due to the rapid development of supporting technologies such as the Internet of Things, robotics, and big data. The IIoT is a typical implication of Cyber-Physical Systems (CPS) in this era. It strives to optimise resources and improve manufacturing efficiency by connecting physical equipment, collecting large amounts of data, sensing the environment, and automating processes. Decentralisation, anti-tampering, transparency, anonymity, and contract autonomy are all properties of blockchain technology. Huo et al. [75] recently analysed several blockchain implementations for IIoT advancements and examined the technological requirements for blockchain platforms in IIoT applications. The present centralised architecture employed in IIoT is expensive to establish and vulnerable to cyber threats and single-point failure. As a result, more is needed for dependable production within the framework of Industry 5.0. Researchers are presently exploring a secure middleware solution for the decentralised Industrial Internet of Things (IIoT) that utilises the auditing and tamper-proof functionalities of blockchain technology to ensure the reliability, authenticity, and availability of information. Leng et al. [76] have recently introduced a secure blockchain middleware architecture for decentralised Industrial Internet of Things (IIoT) that can be applied to Industry 5.0 IIoT applications.

Modern intelligent manufacturing systems are under intense pressure to advance from old systems complying with ANSI/ISA-95 Enterprise-Control System Integration or IEC/ISO 62264 standards, abbreviated ISA-95. The manufacturing industry is currently coexisting with old and innovative production systems. This varied ecosystem faces scalability, interoperability, security, and data quality issues. The majority of ISA-95 enterprise functions are amenable to blockchain implementation. Yalcinkaya et al. [77] recently suggested a blockchain reference architecture for both traditional and smart manufacturing systems compliant with international standards like ISA-95. Shared Manufacturing is a novel social manufacturing approach built on the sharing economy's ideas. However, the varied industrial environments pose numerous integration issues. Rožman et al. [78] proposed a scalable framework for blockchain-based Shared Manufacturing that guarantees transaction record openness and immutability, which is crucial to developing trust between entities. By utilising cross-chain solutions, they provide a scalable integration of blockchain technology into the notion of Shared Manufacturing. Their user survey analysis shows that the sidechain implementation is more scalable than the public blockchain network.

Decentralised industrial systems allow for fresh business concepts like machine autonomy and servitiation of production. Integrating distributed ledger technology into the machine-sharing and servitisation economy poses various problems and new research concerns. Pustišek et al. [79] analysed the related data and event models, as well as secure upgradeable smart contract platforms for machine servitisation, and proposed a method for efficiently separating on and off-chain data and ensuring decentralised application

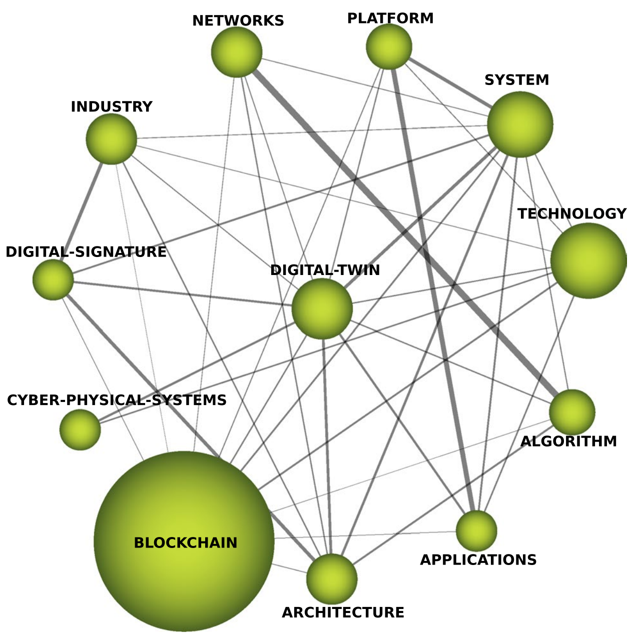



**Fig. 4** A typical cluster of a strategic diagram associated with the current period showing the interactions among various associated themes

scalability without compromising trust. The themes discussed in the leaf nodes [75, 79] indicate the direction of future research.

## 3 Science mapping and knowledge diffusion

While the main path identifies milestone articles based on citations, science mapping [80] detects the chronological evolution of active research area using keyword co-occurrence networks constructed from the retrieved bibliometric data. Science mapping employs a clustering algorithm to reveal the research topics corresponding to each period. The discovered research topics are organised into a strategic diagram based on their centrality and density rank values [80]. The science mapping complements the main path analysis. The chronology was broken into five periods based on the number of publications. The process of science mapping proposed by Cobo et al. [80] provides strategic diagrams showing the relative importance of the research topics during a period and the clusters associated with the themes. The strategic diagrams portray emerging and vanishing research topics during a period. Each such topic is characterised by a network cluster of terms showing their interactions. A typical network cluster of a strategic diagram related to the current period showing the interactions among various associated terms is given in Fig. 4. All these, together, provide dynamics of the evolution in terms research focus of the domain.

The diffusion of knowledge that led to the adoption of blockchain in manufacturing is taken from the complete science map obtained using SciMAT tool [80] and shown in Fig. 5. From 2000 to 2009, most of the studies focused on the architecture of different production systems. From 2010 to 2014, the focus was on system design perspectives. Between 2015 and 2019, major blockchain applications that integrated cloud computing and IIoT emerged. Blockchain integration has introduced many novel ideas to the manufacturing process, raising it to a new level. It also brought new challenges for seamless integration when these advances were adopted. The terms that emerged in the most recent period offer an insight into the industry's present issues and ensuing possibilities, as well as future research directions. Some of the focal themes of active research of the most recent period are depicted in Fig. 5. We examined these terms in detail and discussed the details in the following sections.

## 4 Research themes and their interdependence

Smart manufacturing development involves various technologies, from sensors for the Internet of Things to policy formation based on International standards. Therefore, it is

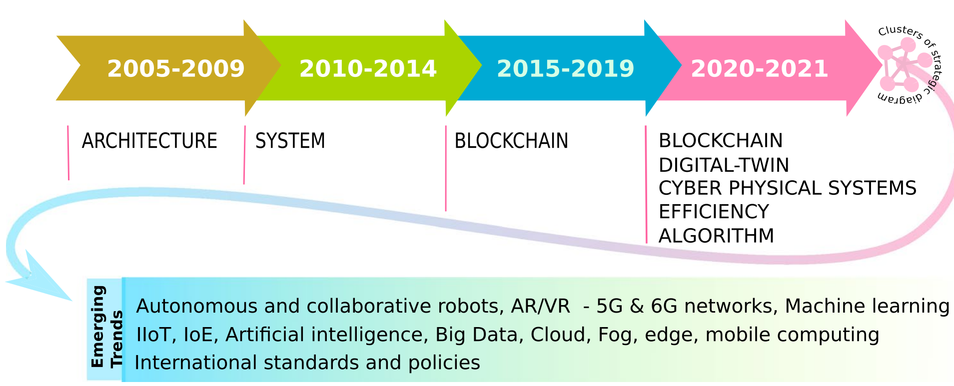



**Fig. 5** The science mapping of theme-wise evolution of blockchain technology in manufacturing. The future trend was extracted from the corresponding period's strategic diagram associated with clusters

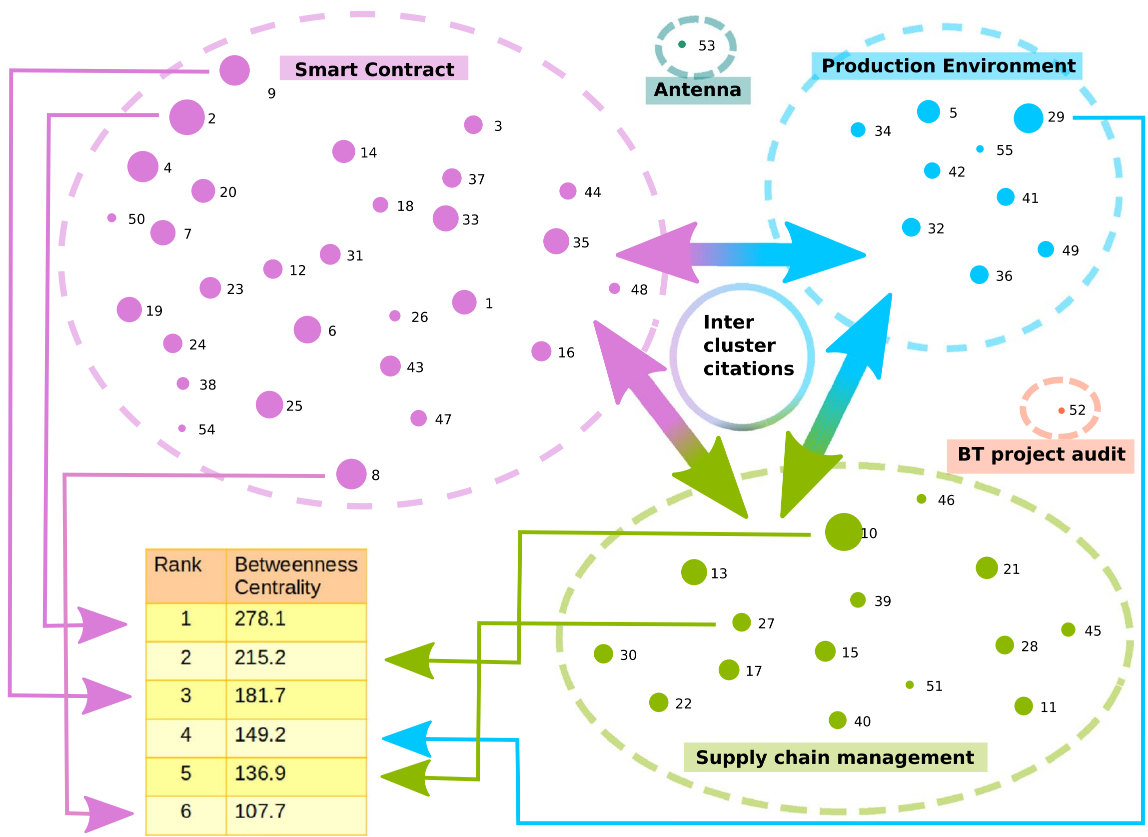
interesting to analyse various subdomains in this field. Thus we carried out a clustering analysis of the citation network based on the Louvain topological clustering algorithm [81]. Blondel et al. [81] developed the Louvain method for community detection, which is a technique used to extract communities from large networks. The approach is based on the optimisation of modularity given by

$$Q = \frac{1}{2m}\sum_{ij}\left[A_{ij} - \frac{k_i k_j}{2m}\right]\delta(c_i, c_j) \tag{1}$$

during the algorithm's progression. In Eq. 1, $A_{ij}$ is the edge weight, $k_i$ and $k_j$ are the sums of the weights of the edges attached to nodes $i$ and $j$, $c_i$ and $c_j$ are the communities and $\delta$ is the Kronecker delta function. Modularity, a scale value ranging from −0.5 to 1, represents the relative density of edges within communities compared to outside communities. The algorithm's objective is to optimise modularity, which measures the density of links within communities versus links between communities.

The clustering of the citation network extracted 55 clusters representing subdomains. Each cluster is shortened to create a cluster node, represented by the cluster's most-cited article. Inter-cluster article citations link the cluster nodes. The clusters are shown in Fig. 6. We used schematic arrows to substitute the edges generated by inter-cluster citations to avoid clumsiness. The content analysis of these representative articles would give an idea about the general theme of the cluster. In the network of these clusters, the edges represent the citation of articles between clusters. The double-headed arrows in Fig. 6 schematically represent the citations of papers in one cluster by articles in another. The clustering of the network of clusters is shown in Fig. 6 by the node colours. The nodes with the same colour indicate that the study topics are comparable. One of the main objectives of this clustering process is to identify the subdomain of research in this area, which would have a future impact.

The betweenness centrality of a node in a network is a measure of the number of times the node lies in the shortest path between other nodes. It can also be thought of as a




| Rank | Betweenness Centrality |
|---|---|
| 1 | 278.1 |
| 2 | 215.2 |
| 3 | 181.7 |
| 4 | 149.2 |
| 5 | 136.9 |
| 6 | 107.7 |

**Fig. 6** Clusters of the citation network representing articles with common themes. The network of clusters illustrates inter-cluster citations, with each node representing a cluster and the size indicating inter-cluster citations. The colours of the nodes depict clusters with similar themes. Pink clusters focus on smart contracts, the blockchain of things (BCoT), and edge computing. Green clusters address supply chain management issues, while blue clusters explore factors related to production and manufacturing, such as IIoT, digital twins, servitisation of business, cyber-physical production systems, and artificial intelligence solutions. Clusters with high betweenness centrality hold potential for future innovations. See Table 1 for article details corresponding to each node number

measure of how important a node is to the spread of information through the network. The betweenness centrality of nodes in a citation network has been used to determine the most promising research paper in a given field [47]. We extend this notion to the network of clusters linked by article citations to find the research topics that will drive future innovations. Except for six cluster nodes, the betweenness centrality of the remaining nodes is less than 60. They are indicated in Fig. 6. The cluster with the highest ranking is focused on smart contracts. This observation shows that smart contract difficulties have not been resolved and will draw more research initiatives. The cluster with the highest ranking is focused on smart contracts. It indicates that problems surrounding smart contracts have not been resolved and will draw more research initiatives in the future. Many contemporary solutions lack transactional privacy. The blockchain records all transactions, including money movement between pseudonyms and the amount exchanged. Kosba et al. [82] recently advocated a solution to be adopted by the community to address these issues.

The sustainability issues are the main concerns discussed in the second cluster in ranking. Pressures from the community, consumers, and local and global governments to fulfil sustainability targets encourage researchers to look at how blockchain might solve and help in the sustainability of social manufacturing. Saberi et al. [83] have examined the importance of Blockchain technology and its connections to sustainable supply chain management. The IoT has enormous promises for advancing industrial production to the next level. However, owing to security difficulties and poor interoperability, incorporating IoT into the decentralised manufacturing process poses several obstacles. The cluster with the third-largest betweenness centrality discusses primarily the issues related to IIoT. Wang et al. [84] proposed the architecture of coupling an IoT with blockchain to overcome many of these issues. They coined the term blockchain of things (BCoT) to represent such models. The critical problems covered in the fourth cluster are those of sustainability. According to Lu [12], blockchain has the potential to play a major role in global sustainable development by providing high scalability and interoperability across the intellectual and physical worlds.

The food supply chain is a complicated system comprised of several players, including farmers, manufacturing plants, distributors, retailers, and consumers. One of the primary causes of food fraud is a mismatch in information between these diverse partners. Numerous solutions that use blockchain technology in the food delivery supply chain are mainly concerned with food safety and traceability. Another major topic the paper addresses in the fifth cluster that gets the most citations from publications in other clusters is the efficacy of supervision and management of the food supply chain [138]. The top paper in the 6th cluster discusses peer-to-peer energy trading systems assisted by blockchain. Ali et al. [139] presented three blockchain-based energy-trading models to overcome technological obstacles and commercial constraints and accelerate the implementation of this innovative technology. The topic of investigation in these clusters with high betweenness centrality can lead to future innovations.

Let us now broadly look at the topics of investigation of all these clusters. Some of the major themes of the pink clusters are smart contracts, transactional privacy of smart contracts as blockchain records all transactions details such as the amount exchanged between pseudonyms [82, 140], attacks on Ethereum Smart Contracts [115], integration of IoT with blockchain [84], fundamental and circumstantial bottlenecks of networks to support substantially higher throughputs and lower latencies [141], Cyberphysical Blockchain-Enabled Energy Trading [139], anti-counterfeiting measures for additive manufacturing [64] and edge computing [142]. While Kosba et al. [82] raised concerns about the transactional privacy of smart contracts, pointing out that the blockchain preserves all transaction data, including the amount transacted between pseudonyms, Zheng et al. [140] evaluated many popular smart contract platforms and provided a classification of smart contract applications, as well as some exemplary instances. According to Miller [143], blockchain and IoT are critical technologies that will significantly influence industrial enterprises during the next decade. A decentralised energy-trading system uses several sources and efficiently organises the energy to guarantee the best use of available resources. Ali et al. [139] examined the feasibility of implementing blockchain to overcome technical and economic constraints. Zhang et al. [142] highlighted the advantage of a configurable and secure edge service management solution powered by edge intelligence and blockchain in a recent article. The numerical results of their proposed models indicate that the proposed methods lower the cost of edge services while increasing service capacity. Another notable work in this block of clusters is the method of coupling lanthanide nanomaterial chemical signatures with blockchain technology for countering parts counterfeiting for additive manufacturing [64].

The green clusters include a broad range of topics related to supply chain management. Some of the main topics of these clusters are credit assessment method to enhance the performance of food supply chain monitoring and supervision [138], sustainable supply chain logistics and management [83, 112], blockchain technology for the smart applications [144], blockchain performance [145], blockchain and additive manufacturing [94] and online alarm management systems [146]. The main issue with food supply chain management is the information asymmetry associated with the stakeholders ranging from farmers to retailers. Most of the supply chain systems studies focus on traceability. Recently,

**Table 1** Themes of the representative papers in each cluster shown in Fig. 6

| Node | Theme | References |
|---|---|---|
| 1 | Blockchain Market worth | Singh [85] |
| 2 | Privacy-preserving smart contract | Kosba et al. [82] |
| 3 | BT for IoT, Smart home | Dorri et al. [86] |
| 4 | Decentralised blockchain | Croman et al. [87] |
| 5 | Industry 4.0 and Supply Chain | Tjahjono et al. [88] |
| 6 | Anti-counterfeiting, additive manufacturing | Kennedy et al. [89] |
| 7 | Challenges and advances of smart contracts | Zheng et al. [90] |
| 8 | Blockchain-enabled energy trading | Ali et al. [91] |
| 9 | IoT | Dai et al. [92] |
| 10 | BT and supply chain | Saberi et al. [93] |
| 11 | BT and additive manufacturing | Kurpjuweit et al. [94] |
| 12 | BT and smart energy grids | Pop et al. [95] |
| 13 | BT, Credit evaluation system, food supply chain | Mao et al. [96] |
| 14 | Security and privacy on blockchain | Zhang et al. [97] |
| 15 | BT and Industry 4.0 | Bodkhe et al. [98] |
| 16 | Reputation system, IIoT, retail marketing | Liu et al. [99] |
| 17 | supply chain traceability, BT, IoT | Tian [100] |
| 18 | Blockchain Standards | Anjum et al. [101] |
| 19 | Scalable IoT Business Blockchain | Biswas et al. [102] |
| 20 | BT and IoT in industry | Miller [103] |
| 21 | digital technology and Industry 4.0 | Ivanov et al. [104] |
| 22 | Data Processing and BT | Dinh et al. [105] |
| 23 | BT and Cyber-Resilient Automotive Industry | Fraga-Lamas and Fernández-Caramés [106] |
| 24 | BT and multi-agent symbiotic CPS | Skowroński [107] |
| 25 | Edge Intelligence, BT, 5 G, IIoT | Zhang et al. [108] |
| 26 | BT, Supply chain, ERP | Banerjee [109] |
| 27 | BT and supply chain resilience | Min [110] |
| 28 | BT and enterprise operational capabilities | Pan et al. [111] |
| 29 | BT issues | Lu [12] |
| 30 | BT, physical internet, sustainability | Treiblmaier [112] |
| 31 | Issues of proof-of-authority based BT | Ekparinya et al. [113] |
| 32 | Servitization of business | Vandermerwe and Rada [114] |
| 33 | Attacks on Ethereum smart contracts | Atzei et al. [115] |
| 34 | Agent-based distributed manufacturing control | Leitão [116] |
| 35 | Peer-to-Peer Electronic Cash System | Squarepants [117] |
| 36 | BT and AI | Swan [118] |
| 37 | BT and privacy | Ma et al. [119] |
| 38 | BT-enabled smart contracts, applications | Wang et al. [120] |
| 39 | BT Research Framework | Risius and Spohrer [121] |
| 40 | BT and its social impact | Al-Saqaf and Seidler [122] |
| 41 | Cyber-physical production systems | Lu and Xu [123] |
| 42 | Mobile cloud computing | Fernando et al. [124] |
| 43 | Service quality, BT, IIoT | Maiti et al. [125] |
| 44 | IoT security | Khan and Salah [126] |
| 45 | 3-D printing | Berman [127] |
| 46 | AI and education | Marr [128] |
| 47 | BT and healthcare | Hasselgren et al. [129] |
| 48 | Illicit Bitcoin transactions | Irwin and Turner [130] |
| 49 | Cloud computing | Mell and Grance [131] |
| 50 | Support-vector networks | Cortes and Vapnik [132] |

**Table 1** (continued)

| Node | Theme | References |
|---|---|---|
| 51 | Smart alarm systems for industry 4.0 technologies | Chang [133] |
| 52 | Auditing method | Lee and Park [134] |
| 53 | Antennas arrays | Angeletti and Toso [135] |
| 54 | Mobile low power wireless sensor networks | Gaddour et al. [136] |
| 55 | M-Health solutions using 5 G networks | De Mattos and Gondim [137] |

techniques for analysing the efficacy of supply chain supervision have gained interest. Smart applications in smart farming, healthcare, supply chain and logistics, travel and hospitality, and energy management are rapidly gaining prominence. Despite this fact, the open nature of the channel causes security and privacy concerns for all of these applications. Many suggested application security solutions are either centralised or too costly to deploy owing to high computing and communication expenses. Blockchain technology may alleviate some of these issues. Industry uses either public or private blockchain platforms. The performance of these chains regarding workload is another concern for the business. Social, environmental, and economic variables are used to assess supply chain sustainability (or the three Ps: people, profit, and the planet). Treiblmaier [112] suggested a theory-based specific area for future study to solve supply chain sustainability challenges by combining the physical Internet with blockchain. A recent Delphi study on additive manufacturing adoption indicates potential relating to intellectual property rights management, tracking printed product lifecycles, process improvements, and data security [94]. The main obstacles to AM blockchain implementation are the need for blockchain-skilled individuals, governance structures, and firm-internal technological skills. Chang [146]examined the quality of online real-time early warning systems for production and raw material supplier management, intending to increase the intelligence of a large data blockchain-based production and managing product traceability.

The blue clusters are mainly concerned with the production and manufacturing environment. The main focuses are on role of blockchain on IIoT and the compatibility issues [12], digital twines [147, 148] and servitization of manufacturing [114]. In the manufacturing sector, blockchain is often coupled with IoT, providing a great opportunity to establish data security and trust for automation, intelligence development and an un-centralised programmable smart ecosystem [12]. The introduction of the Internet of Things (IoT) into the production and manufacturing environment was a paradigm shift in the manufacturing industry [149]. The definition of IoT is evolving as its applications proliferate [150]. However, the adoption of blockchain in IoT faces several obstacles in terms of connection, the trade-off between performance and power consumption, a compromise between throughput and concurrency, transparency and privacy, massive data management, and blockchain regulatory concerns [151]. The digital twin is another revolutionary technical intervention brought into the manufacturing industry. Organisations can achieve data-driven operation monitoring and optimisation, produce novel products and services, and diversify value generation and business models by using Digital Twin and intelligent algorithms [152]. Adoption of digital twins in conjunction with blockchain, on the other hand, raises many obstacles, including interoperability, affordability, precise representation of an item, scalability, data privacy, and legal and ethical concerns that must be addressed in the future [153]. Manufacturing servitisation is the process of moving from selling goods to selling a Product-Service System. Investing in servitisation has reportedly had mixed results. Increasing sales revenue, poor service quality and the high expense of changing current organisational structures and processes are some of the main reasons for the poor performance of servitisation of manufacturing. It has also been reported that lean production could be used in servitisation to improve a manufacturer's efficiency and effectiveness. Recent studies have shown that lean bundles and servitisation complementarily impact long-term performance. Still, the mechanisms by which organisations coordinate these practices to achieve complementarity need to be clarified [154].

The topological structure of the strategic diagram obtained by keyword co-occurrence in Fig. 5 shows that most themes are connected. The star topology with a digital twin at its centre connecting all other themes shows its relative importance. The relatively large node representing blockchain shows its importance in the environment. It also connected most of the nodes except CPS. Besides, the themes represented by clusters shown in Fig. 6 also offer strong connections among the clusters barring antenna research and BT project audit. Though the field has multidisciplinary characteristics, many components such as BT, security and privacy, and network resilience are relevant in different segments in the area *viz.* smart contract, production environment and supply chain management.

In summary, the citation network cluster analysis provides the following findings. First, the relatively high number of linked clusters, except for two isolated clusters on antennas and blockchain project auditing, demonstrates the involvement of various research subjects in developing manufacturing scenarios. This variation might be attributed to diverse technologies and the problems of seamless integration. The substantial number of cross-cluster citations highlights the interdependence of diverse technologies and challenges. Second, the expansion of distributed manufacturing via various technologies is still in its early stages. This point was also mentioned by several writers [155–158]. Third, the clusters with high betweenness centrality indicate that smart contracts, supply chain management, the Internet of Things (IoT) and associated sensors, and sustainable manufacturing will be the focus of future research and innovation.

## 5 Roadmap and conceptual evolution model

The comprehensive analysis of the main path of evolution and scientific mapping delineates the future trajectory of blockchain technology's role within manufacturing sectors, as illustrated in Fig. 7. In later stages, a substantial shift of blockchain from being a supportive technology to forming the crucial infrastructure of industrial production and supply systems was observed. This transition was bolstered by the parallel progression of technologies such as 5 G, facilitating the integration of various innovations from smart contracts to data provision for constructing AI models with autonomous decision-making capabilities. Throughout this period, significant advancements were noted in blockchain technology pertaining to resources, processing power, interoperability, portability, and scalability. However, to attain standards of privacy-preserving, interoperable, energy-efficient, AI-aided hybrid blockchains, further development is warranted [159]. Blockchain's evolution as a technology has undergone multiple phases. Initially introduced as a decentralised public ledger, the Blockchain 1.0 era is characterised by digital currency, with Bitcoin being a prominent instance. Blockchain 2.0 featured smart contracts as its core component, underpinned by a consensus mechanism, information encryption, and decentralised applications (DApp). This era witnessed the emergence of several public blockchains, including Ethereum, TRON, IOST, and NEO. Widespread blockchain technology implementations and the convergence of value internet and real economy mark the ongoing Blockchain 3.0 economy.

Decentralised Autonomous Manufacturing (DAM), a paradigm utilising decentralised technologies, including blockchain and smart contracts, orchestrates a fully automated manufacturing process. Within DAM, the manufacturing machinery is integrated with blockchain networks, ensuring secured and transparent data exchange governed by smart contracts [160]. Decentralised Applications (DApps), running on blockchain networks, facilitate a high degree of automation and efficiency in DAM-based manufacturing, with assurances of transparency and security. A salient advantage of DAM is the reduction in human intervention leading to swift and economical production, and with the inclusion of blockchain, data integrity and fraud prevention are enhanced.

The advent of Industry 4.0 instigated changes in the abilities needed at nearly all manufacturing hierarchical levels [161], paving the path for Industry 5.0, where humans and robots collaboratively work, placing the human element at the core. Industry 6.0 envisions renewable energy, ultimate machine autonomy, interplanetary resource collection, aerial manufacturing, anatomical enhancements, and quantum control [162]. Industry 5.0, emphasising human-centred manufacturing systems, strives for societal goals transcending mere employment and growth, targeting substantial prosperity for the sustainable development of all humanity. Anticipated to be pivotal are human-centricity, sustainability, and resilience. Blockchain technology can underpin Industry 5.0 through secure, transparent, and decentralised platforms for data sharing, transaction management, and process automation. Blockchain-based digital identity solutions, a specific application towards Industry 5.0, can augment the security and privacy of data sharing and collaboration within manufacturing ecosystems. This approach employs decentralised

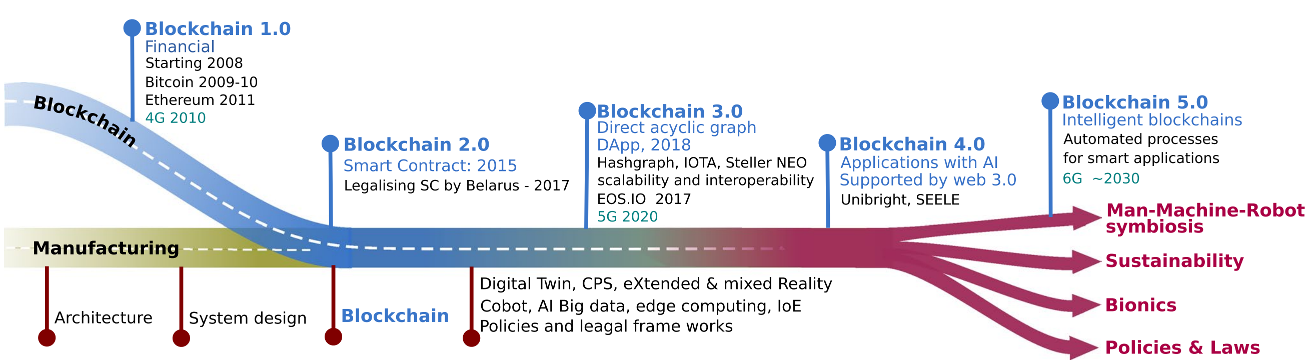



**Fig. 7** The roadmap for the advancement of manufacturing through the use of blockchain technology

identity systems, empowering individuals and organisations with control over their identity data and facilitating secure, seamless authentication across varied systems and networks. Smart contracts secure enforcement, access control, authentication, and service-oriented behaviour automation play crucial roles in Industry 5.0 supply chains. The contract low-level interfaces mechanise agreements between stakeholders, smart contracts, and blockchain networks.

Retrospectively, Industry 5.0 can be viewed as an extension of the trends initiated by the first industrial revolution. While Industry 1.0 introduced mechanisation, Industry 2.0 brought mass production, and Industry 3.0 introduced automation. Subsequently, Industry 4.0 introduced cyber-physical systems and the Internet of Things (IoT). Expanding on these advancements, Industry 5.0 emphasises the integration of humans and technology, fostering a more comprehensive approach to manufacturing [160].

### 5.1 Roadmap ahead

In the future of manufacturing, specifically in the centralised control of numerous interconnected heterogeneous devices, blockchain technology continues to offer significant improvements in confidentiality and transparency. The three generations of blockchain identified by Swan [11] and Zhao et al. [163] are as follows: blockchain 1.0 enabled digital cryptocurrency transactions, blockchain 2.0 introduced smart contracts and applications beyond digital transactions, and blockchain 3.0 improved its potential in terms of transaction time, scalability, and ease of implementation through decentralised applications (DApps). This study proposes a roadmap model exclusively related to the applications of blockchain technology in the smart industry, which suggests three stages of evolution.

### 5.2 Functions of future blockchain

The milestone articles on the main path suggest that blockchain-enabled manufacturing research in the future will focus on sustainable, environmentally friendly, and zero-waste manufacturing processes, as this technology instils trust, authenticity, and transparency in these components. Supply chains serve as the backbone of all manufacturing businesses, and most of these chains can benefit from the blockchain's block-based approach to enhance efficiency and safety. These chains would aid manufacturers in meeting delivery dates and improving product quality, thereby increasing sales. Blockchain can also be employed to track the number of products produced to ensure compliance with agreed-upon and purchased quantities, mitigating piracy. In the future, blockchain-enabled systems will assist users in verifying the sustainability of products, including their sources, procurement, and production. Blockchain has the potential to introduce an entirely new manufacturing business model by enhancing visibility across all stages, from production to sale, encompassing sourcing, machine-level monitoring, and shop floor operations. Cluster analysis indicates that blockchain technology is expected to have a broader impact in enabling the industrial Internet of Things.

Additionally, as public blockchains become more accessible and cost-effective, public blockchain technology utilising the public cloud is anticipated to receive increased research attention. Cluster analysis also reveals blockchain applications in cloud manufacturing, facilitating a secure, authenticated, and verifiable network for service sharing on the cloud between providers and end-users [164, 165]. The lockdowns resulting from the COVID-19 pandemic have compelled manufacturers to explore alternative and more efficient production processes. Moreover, blockchain applications in intelligent manufacturing, smart factories, cybersecurity, and the industrial Internet of Things are growing, indicating that this trend is expected to continue in the future. These patterns illustrate the immense potential of blockchain in revolutionising the future of industries.

### 5.3 Cobots

The use of blockchain technology as a communication tool for a robot team could provide security and protect against deception. Collaborative robots are designed to operate alongside humans, making human capabilities more efficient and accessible to individuals and small businesses. Unlike Industry 4.0, which focuses on cyber-physical system connectivity, Industry 5.0 connects applications and collaborative robots (cobots). In high-volume manufacturing, robots are superior to humans and are far more compatible. The earliest cobots had no engines, were highly passive, and were equipped with brakes. Unlike classic industrial robots, modern cobots may collaborate with humans without enclosures. Cobots are typically equipped with sensors that detect unanticipated collisions, allowing them to stop independently when human workers intervene. These sensor-equipped robots make them safer at work compared to standard industrial robots [166]. Personalisation and customisation of items may be a significant future difficulty for robots requiring guidance. Consequently, the management of human intervention in industrial processes is vital. For humans and robots to collaborate, robots' motion controllers must be able to anticipate human actions and intentions and adjust accordingly. Future researchers are anticipated to concentrate heavily on this aspect of cobots' use in production. One area that requires further attention is human action intention prediction [167].

Decentralised decision-making has piqued the interest of many researchers. However, only some studies have examined when decentralised material handling is more profitable or more effective than centralised control. Additional research is needed in the field of autonomous robots to evaluate and compare centralised vs decentralised control and global vs local optimisation, as well as to investigate the various levels of autonomy in decision-making. Furthermore, more research is needed to determine how decentralised control affects profit, resource efficiency, responsiveness, latency, and system robustness and dependability [168].

### 5.4 The eXtended reality

The eXtended Reality (XR) technology, a hybrid of Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), will be critical in next-generation applications. XR is currently used in various domains, including remote assistance and assembly line monitoring. By combining the virtual and physical worlds, XR can further improve human–machine interactions and more effective deployment of cobots in the future [166]. The sixth-generation networks (6 G) could provide major value-added services. Connecting hardware elements and robots with the present infrastructure is complex. Existing networks will be unable to handle the constantly expanding bandwidth demands of smart infrastructure and prospective applications. Using 6 G allows for better latency, high-quality services, broad IoT infrastructure, and integrated AI capabilities [169]. Production management has already embraced the industrial Internet of Things. The next step would be to use the Internet of Everything (IoE), which connects people, processes, information, and things. In terms of decentralised management, operational transparency, compartmentalised production, and creating digital identities, IoE can be a game changer for next-generation applications [170–172].

### 5.5 Fog and edge computing

Fog computing, which was proposed in 2011, extends cloud computing technology to the network's edge [173]. Fog nodes act as a layer between cloud servers and network edge nodes. Edge computing (EC) is a concept that allows data processing at the network edge. Data security and privacy are achievable with EC. In addition, it ensures remote application productivity. Also, EC can process data without sending it to the cloud, lowering future security risks and maintaining cache coherency, offload computing, transferring data, and delivering requests. All of these network operations require a private, secure edge. Low latency, data security and privacy are EC's top priorities. EC can support preventive analytics, allowing for early detection of machine failure and reducing downtime by empowering workers to make informed decisions. Constant process improvement requires detailed information about the entire manufacturing cycle. Big Data Analytics can identify and eliminate non-essentials to increase predictability and discover new possibilities. It can help with mass customization processes with zero-fail resource integration. Decision-makers at the managerial level can benefit from using big data analytics and artificial intelligence to support the principles of risk pooling, socio-ecological process learning, process agility, and responsiveness. This facilitation can be achieved through demand analytics, real-time supply chain control, flexible capacity, risk-mitigation inventories, backup-transportation routes, multiple sourcing, product substitution, and multiple suppliers. For example, Barenji et al. [174] presented a platform to support consumer views, scalability, and security using machine learning techniques like support vector machine (SVM), fog computing, and blockchain technology. SVM classifies customer views, fog computing improves efficiency and reduces latency, and blockchain technology provides secure data exchange. At the operational level, artificial intelligence can greatly assist in learning decision policies, detecting dangerous situations, forecasting optimum parameters and uncertainties, user preferences, and system functions [175]. It is possible to solve the storage problem by merging artificial intelligence with existing optimization algorithms to improve computational power efficiency and to systematically delete the irrelevant data of blockchains [37]. Machining is another area where deep learning has remarkable opportunities [176, 177].

### 5.6 Policy formulation and legal framework

Another area which needs attention is the formation of international standards and policies for the rapid developments in automation. An ISA standards committee developed ISA-95. It describes how enterprise operations, including data models and exchange definitions, can share electronic information. ISA-95 guides both off-the-shelf and specialised production systems. The ISA-95 standard unifies manufacturing execution systems (MES), enterprise resource planning (ERP), IIoT, data lakes, and analytics. A unified namespace (UNS) facilitates corporate data integration. How long ISA-95 would be valid with rapid developments and technology adoption in manufacturing is a question to be addressed. The scheduling of a production system has long been studied, resulting in numerous scheduling mathematical formulations and policies. These efforts are mistakenly directed toward MES scheduling due to the ISA-95 layered architecture, which ignores obvious synergies for objective optimisation between the field control layer and MES scheduling. More machine parameters are becoming accessible and adjustable as cyber-physical system technology evolves in the industry. In traditional ISA-95 architecture, the control layer can expand the scheduling layer's decision space. The new cyber-physical production system (CPPS) manufacturing architecture views scheduling and control as a joint optimisation of scheduling and control problems (JSC) [178]. The ISA-95 model's components determine vertical domain interaction. The current ISA-95 Model does not incorporate all vertical integration components, such as product domain. Ideal CPS structure requires information technology (IT) and operational technology (OT) components in all ISA-95 tiers. Recently Apilioğulları [179] proposed an extended ISA-95 Model which identifies all CPS components required for project-based manufacturers. By adding a product domain and connection layer to ISA-95, any manufacturing sector may utilise it in digital transformation.

In the context of the circular economy, blockchain was introduced to secure data to gain the confidence of value chain partners to participate in the manufacturing supply chains. Despite blockchain's benefits, implementing it into remanufacturing takes time and effort. Practitioners often question how well remanufacturing contracts and data were safeguarded. Despite data dependability, information management needs more legal security. This issue was investigated by many authors [180–184]. As we advance toward a circular economy by incorporating developing technology, the legal framework and standards will remain a topic of considerable interest. Current technology advances must coexist with the regulatory sector to provide regulated, controlled functioning within the confines of the law. Additionally, more tasks being taken over by AI would need legislative amendments to address ambiguous instances.

### 5.7 Bionics

Bionics is expected to be a significant component in the manufacturing industry in the context of mass personalisation in the speculated Industry 6.0. The advent of novel raw materials, such as the utilisation of algae for photovoltaic coatings, will speed the development of second-generation bio-products through interdisciplinary efforts. Bionics-based machining is also gaining popularity [185–187]. The competition in the field has also been promoted by conducting events such Bionic Olympics. Research is currently focused on various aspects ranging from multisensory integration in bionics to Bionic Banking. Bionic robots would play a remarkable role in the industry. A single intelligent bionic robot cannot perform future jobs. Complex duties necessitate the robot not just navigate field obstacles and cooperating with other robots in a multi-robot system. As a result, research into multi-robot control systems for spherical amphibious robots is vital and will be continued further. Blockchain-based decentralised amphibious multi-robot control systems require future attention. Experts have already speculated that by the year 2050, technology will have progressed to the point of complete autonomy. The retrogressive road to Industry 6.0 predicts coexisting robots. Previous revolutions centred on technical automation and customised manufacturing are expected to culminate in monolithic manufacturing houses where machines are tied into diverse task-specific AI algorithms to create on a consumer-request basis. The sixth revolution will integrate multidimensional printing, robo-medics, assistive home-robotics, cumulative-alternative energy, and deep-dive EEG for boosting productivity and living quality [162].

### 5.8 Federated and split learning

Blockchain and Federated Learning could transform many industries in terms of data sharing, security, and privacy. Federated Learning enables several devices to train a model without transferring data which is specifically useful in the case of sensitive data. Federated Learning and Blockchain safeguard privacy, security, and transparency. Combining the technologies ensures data privacy and provides machine learning model insights [188, 189].

One example of a blockchain-based Federated Learning system is the Federated AI Blockchain Environment (FATE) framework. FATE is an open-source framework for secure and transparent collaborative machine learning employing a consortium blockchain to ensure tamper-proof transparency. Another example is the HealthChain project, a blockchain-based Federated Learning platform for medical data analysis. It helps hospitals share medical data securely. Federated Learning trains machine learning models cooperatively, and a blockchain-based architecture secures and transparently stores data [190]. The relationship between blockchain and Federated Learning is promising, with the potential to transform various industries by enabling secure, transparent, and privacy-preserving data sharing and collaborative machine learning. As more organisations recognise the importance of data privacy and security, we expect to see more applications of blockchain-based Federated Learning in various fields.

Another approach is to adopt split learning for several parties to train a model without sharing data. Split learning trains the model on a central server while data stays on client devices. This method protects data without risking unauthorised access or theft while allowing several parties to contribute to a shared model. The combination of split learning and blockchain has the potential to transform a variety of industries. For example, split learning can enable healthcare organisations to collaborate on developing new treatments and therapies without exposing patient data to unauthorised access. In the financial sector, split learning and blockchain can be used to develop more accurate risk models and improve fraud detection. In cybersecurity, split learning and blockchain can be used to develop more secure and robust security systems [191]. Recently Khan et al. [192] proposed a federated split learning model for Industry 5.0 to avoid data poisoning attacks. These advanced ML technologies enable manufacturers to increase productivity, reduce costs, and improve the quality of their products.

### 5.9 Production autonomy

The Blockchained Smart Contract Pyramid-Driven Multi-Agent Autonomous Process Control (BSCP-MAAPC) approach integrates blockchain, smart contracts, multi-agent systems, and process control to establish a resilient and personalised manufacturing process. The pyramid structure of the BSCP-MAAPC approach manages different levels of control, from physical machines to abstract control systems. Multi-agent systems enable adaptability and dynamic adjustments based on the manufacturing process's current state. Leveraging blockchain ensures transparency and security, facilitating effective collaboration and coordination among diverse agents in the manufacturing process [193].

Achieving total autonomy in production requires further research, with a focus on intelligent blockchains powered by AI. Balancing privacy and data accessibility for system enhancement is a key consideration. Interoperability challenges and energy consumption of public blockchains require additional investigation, including energy efficiency and renewable energy integration. New business models, improved decentralised applications, privacy, security, and emergent situations related to material collection and blockchain-connected end-users need further study. Network research will be vital in transitioning from the Industrial Internet of Things (IIoT) to the Internet of Everything (IoE). Advancements in eXtended Reality for human–machine interactions, data analytics using big data and AI for automated decision-making, and fog computing will continue to be research priorities. Establishing symbiotic scenarios of decision-making cobots and human employees involving customers within an Internet of Everything framework will be a focus of active research. Policy formulation and developing a legal framework to address forthcoming technological breakthroughs are areas of future study interest.

## 6 Conclusions and key messages

In conclusion, this research article has examined the importance of blockchain in the manufacturing industry and its evolution through different phases. Analysing a corpus of research literature has provided insights into the growing research fronts, various themes, and paradigm shifts in blockchain technology. By employing social network analysis tools, such as scientific mapping and citation network clustering, the study has depicted the knowledge structure of the field and identified key sub-domains.

The three phases of blockchain development in manufacturing were identified as authentication and anti-counterfeiting, smart manufacturing, and intelligent and sustainable manufacturing. Theme-based progression supported these phases, as revealed through science mapping analysis. The citation network clusters analysis also helped identify similarities between diverse study topics, enhancing our understanding of the subject.

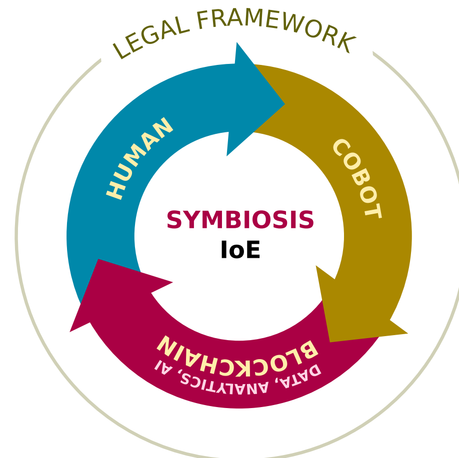



**Fig. 8** The conceptual evolution model indicates a sustainable phase of human-cobot collaboration backed by intelligent BT under supporting policies and regulations

It is important to note that the primary methodology employed in examining the research corpus was citation network analysis, which has been widely used in various domains. However, it is essential to consider that the methodology's effectiveness relies on the number of citations, assuming that a paper's contribution is reflected in its citation count. Moreover, the text's seniority can also influence citation patterns. Overall, this research provides valuable insights into the development and trends of blockchain in the manufacturing industry, contributing to a deeper understanding of the field and highlighting areas for further research and exploration.

Some of the key messages the research reveals are that Blockchain technology (BT), initially used for counterfeit product detection, has become vital for modern manufacturing, improving reliability and playing a pivotal role in AI-assisted analytics. BT's evolution points to its significant role in the future Internet of Everything stage. Emerging technologies like eXtended Reality and cobots are becoming prevalent in production, while fog computing advances decentralized decision-making. Bionics also show promise for future industries. However, policy and legal frameworks pose challenges to these advancements. A conceptual model (Fig. 8), developed based on the preceding discussions, suggests a symbiotic future phase of manufacturing with BT facilitating interconnected operations through the Internet of Things, leading to a new era of mass customization.

**Author Contributions** All authors contributed equally.

**Funding** Nil.

**Data Availability** Not applicable.

**Code availability** Not applicable.

## Declarations

**Conflict of interest** The authors declare no competing interests.

**Ethical approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

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