Renewable and Sustainable Energy Reviews 132 (2020) 110112

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey

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ARTICLE INFO

Keywords:
Blockchain
Sustainable manufacturing
Product lifecycle management
Industry 4.0
Sustainability

ABSTRACT

Sustainability is a pressing need, as well as an engineering challenge, in the modern world. Developing smart technologies is a critical way to ensure that future manufacturing systems are sustainable. Blockchain is a next-generation development of information technology for realizing sustainability in businesses and industries. Much research on blockchain-empowered sustainable manufacturing in Industry 4.0 has been conducted from technical, commercial, organizational, and operational perspectives. This paper surveys how blockchain can overcome potential barriers to achieving sustainability from two perspectives, namely, the manufacturing system perspective and the product lifecycle management perspective. The survey first examines literature on these two perspectives, following which the state of research in blockchain-empowered sustainable manufacturing is presented, which sheds new light on urgent issues as part of the UN's Sustainable Development Goals. We found that blockchain-empowered transformation of a sustainable manufacturing paradigm is still in an early stage of the hype phase, proceeding toward full adoption. The survey ends with a discussion of challenges regarding techniques, social barriers, standards, and regulations with respect to blockchain-empowered manufacturing applications. The paper concludes with a discussion of challenges and social barriers that blockchain technology must overcome to demonstrate its sustainability in industrial and business spheres.

1. Introduction

The realization of the United Nations' 17 Sustainable Development Goals (SDGs) is a diverse process and can be categorized into social, economic, and environmental dimensions of sustainability. While manufacturing usually harms the environment, it also has a positive contribution to humanity's needs for comfort and a decent level of life. Sustainability is an attractive strategy for reducing system risk/uncertainty, satisfying individualized consumer demands, saving energy, addressing social responsibility, and increasing resource productivity in the manufacturing sector [1]. A variety of advanced manufacturing models, which involve developing sustainable processes and systems to produce more sustainable products/services, have been proposed, including social manufacturing [2], peer production [3], open production [4], and crowd manufacturing (a development of crowd-sourcing) [5]. Sustainable manufacturing is one of the measures toward "Goal 12: Responsible consumption and production" and "Goal 9: Industry, innovation and infrastructure" in the SDGs. The primary goal of sustainable manufacturing is initially economic sustainability.

Nevertheless, sustainable manufacturing is also vital for sustainable development of the global society because it helps to address global challenges such as the need for renewable energy sources and green buildings [6]. The primary trend of the above sustainable manufacturing visions lies in the new feature of the crowded/clustered/decentralized interconnection of socialized manufacturing resources and open-architecture products, which implies a fundamental reorganization of the cross-enterprise manufacturing network. Sustainable manufacturing vision requires manufacturers to share product lifecycle information and collaborate in an inherently trust-less manufacturing

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https://doi.org/10.1016/j.rser.2020.110112
Received 18 December 2019; Received in revised form 16 July 2020; Accepted 16 July 2020
Available online 28 July 2020

List of abbreviations

Abbreviations	*Descriptions*
BMC	Business Model Canvas
CAD	Computer-Aided Design
CMfg	Cloud Manufacturing
CPS	Cyber-Physical System
DApps	Decentralized Applications
ERP	Enterprise Resource Planning
IIoT	Industrial Internet of Things
IPSS	Industrial Product-Service Systems
MES	Manufacturing Execution System
NFC	Near Field Communication
OEM	Original Equipment Manufacturers
P2P	Peer-to-Peer
PLM	Product Lifecycle Management
RFID	Radio Frequency IDentification
SDGs	Sustainable Development Goals
SMS	Sustainable Manufacturing System
SPC	Statistical Process Control

network [2]. However, layer upon layer of business negotiations and offline contract signing consume and waste many resources in the lifecycle of production. Current emerging manufacturing paradigms exist in various Internet-based social media, for which secure cyber tools to identify, maintain, and evolve group consensus are lacking; this results in challenges pertaining to confidentiality, trust, and cybersecurity that must be handled. Several critical issues have arisen, including the management of information coordination, product/service manifestation with information complexity, customer demand manifestation with information flow, information vulnerability in outsourcing caused by the limitations of IT systems, and lack of data standards. Moreover, as these issues are compounded with the mass individualization needs of products, the pursuit of sustainability in manufacturing activities is significantly complicated [7]. Erroneous, illegitimate, or tampered data can lead to incorrect conclusions and pose a considerable threat to future cross-linked and value-added manufacturing networks.

Existing trust determination solutions (e.g., Shapeways, Maketime, and Plethora) have connected demanders with providers and facilitated information availability for both parties in terms of capabilities and requirements. Prosumers trust these centralized platforms to provide verified services and cut down the costs associated with outsourcing/crowdsourcing parts to manufacturers [8,9]. However, sustainable manufacturing is often decentralized and carried out by multiple production units and individuals, where each production unit is an isolated information island [10]. Product conceptualization, design, manufacture, and assembly are becoming increasingly complicated because of the increase in socialized manufacturing resources and enabling technologies that participate in this progress. The sharing of product lifecycle information is changing the intellectual property protection and distinctive roles of manufacturers in the network [11]. The production cycle and quality are difficult to guarantee because of weak coordination capability upstream and downstream of the manufacturing community [12]. It is difficult for manufacturers to quickly locate the fault source when quality issues are found, as faults may be caused by a single node or a cohesion between the nodes.

One approach to tackle this issue is the blockchain computing paradigm, which offers a new tool to address the security, sustainability, resiliency, and efficiency of systems. The blockchain offers an innovative decentralized and transparent transaction mechanism (i.e., computational trust). The transparency and traceability characteristics enabled by blockchain and smart contracts show promise for enhancing the sustainability of manufacturing networks, while avoiding intervention from third parties who cannot add value [13]. Practitioners and scholars do not fully recognize the sustainability advantages of blockchain for disrupting the manufacturing sector [14]. Therefore, this paper surveys the current status of blockchain-empowered sustainable manufacturing models and methods. Four keywords (including "blockchain", "sustainable manufacturing", "sustainable product lifecycle", and "Industry 4.0") are utilized for retrieving related research from the Science Direct, IEEE Xplore, Taylor & Francis Online, Springer, Wiley InterScience, Emerald Insight, AIS Electronic Library, Georgia Tech Library, and MDPI online databases. In total, 183 high-quality and relevant papers were manually identified for conduction of a systematic literature review. This survey focuses both on identifying the current status of research on blockchain-empowered sustainable manufacturing and highlighting the challenges and future research opportunities.

The remainder of this paper is organized as follows. Section 2 discusses the benefit of adopting blockchain in the manufacturing industry. Section 3 presents a survey framework for blockchain-empowered sustainable manufacturing. Then, two dimensions of implementing blockchain in sustainable manufacturing are analyzed in the following two sections, respectively. Challenges are presented in section 6, and Section 7 summarizes the conclusions.

2. Sustainability advantages of blockchain in the manufacturing sector

2.1. Blockchain computing paradigm

Blockchain enables the underlying structure of a database with a combination of data blocks and hash chains. The integration with timestamp technology makes existence-proof reliable. A blockchain is characterized by its consensus protocol, which facilitates constant updates of the blockchain. When a new data transaction has been added to a block of the chain, all the data copies possessed in other distributed nodes should update synchronously. Depending on the specific blockchain application, various consensus protocols can be chosen concerning security and efficiency requirements. Blockchain builds trust utilizing the mathematical principles of asymmetric cryptography, which allows users to make a deal with partners, even if they do not know each other. Blockchain can be integrated with programmable smart contracts, which ensures that the uploaded program can credibly and automatically execute the preset logic through self-limitation and security encryption.

Blockchain computing has gone through three stages of evolution so far [15]. Blockchain 1.0 can program digital currency. It established the issuance, distribution, and adjustment mechanisms of digital currency through distributed ledger encryption technology. Bitcoin can be regarded as the first digital currency application of blockchain. Blockchain 2.0 refers to programmable smart contracts. Blockchain 2.0 is a platform on which anyone can upload a program and make the program executable by itself. Blockchain 2.0 ensures that the uploaded program can credibly and automatically execute the preset logic through self-limitation and security encryption. Blockchain 3.0 refers to programmable social governance (also referred to as digital society), which accelerates the creation of more sustainable communities. The synchronization and convenience of data tracking brought about by blockchain can cut down the supervision costs of society. In the long run, the decentralized computing model of blockchain may be able to reshape the entire human society through better cooperation and governance.

Blockchain computing mostly comprises four levels, namely, data storage, consensus algorithm, smart contract, and decentralized application. Among these, the data layer is characterized via cryptography methods, including the Hash algorithm, chain structure, encryption technique, Merkle tree, and timestamp. The consensus layer is the peer-to-peer (P2P) network for the synchronization of distributed data with fault tolerance ability. The contract layer contains programmable contracts automatically executed by the computer to perform the transactions. The application layer provides various programmable manufacturing resources and services.

An intact blockchain-based sustainable manufacturing application includes four components, namely, the machine's digital twin, blockchain agent node, key-value database, and blockchain view manager. The blockchain-based digital twin interacts with other digital twins (e.g., manufacturing execution systems) in cyberspace. The blockchain agent node is hosted at the client to allow for the machine to interact with the blockchain. The key-value database enforces cryptographic proof that the data in the digital twin is tamper-proof. The blockchain view manager is a visualization tool used to trace the transactions on the blockchain system in a human-readable manner. Moreover, the blockchain is often used to provide an interface for other cyber systems, and users can manipulate the blockchain to provide more application services.

2.2. Metrics of adopting blockchain

Blockchain offers a robust and resilient mechanism for distributing and storing record history over the internet. The chain structure links data blocks sequentially in chronological order and thereby ensures that this distributed ledger cannot be tampered with or forged cryptographically [16]. This metric can be used to provide manufacturers with securely shared ledgers that are free from intermediaries [17]. Blockchain also offers the possibility to start new businesses in the manufacturing sector. For a structured discussion of the metrics of adopting blockchain in different situations, the business model canvas (BMC) [18], which includes nine building blocks, is utilized to describe how organizations create, deliver, and capture added value. As shown in Table 1, these nine blocks comprise four domains of business, namely, its customers (including customer segments, channels, and customer relationships), the offer (i.e., value proposition), the infrastructure (including key resources, key activities, and key partnerships), and financial viability (including revenue streams and cost structure). The BMC is introduced as a tool to evaluate the metrics of adopting blockchain in the manufacturing sector.

Regarding infrastructure (i.e., key resources, key activities, and key partnerships), blockchain can facilitate extended visibility, traceability, and disintermediation (i.e., **M1**, the 1st metric listed in Table 1) [19]. Incorporating smart contracts into the blockchain can realize decentralized decision-making and collaborative optimization through P2P interaction in the manufacturing community (i.e., **M2**). The key to reducing the complexities in a dynamic production management is to improve the process flexibility under individualized requirements, which can be achieved by broader resource sharing via blockchain (i.e., **M3**) [20]. According to an experiment that compared networking performance and manufacturing metrics among blockchain-based ManuChain [21], centralized control [22], and agent-based control [23], smart contracts are more flexible and robust with respect to disturbances, individualized requirements, and dynamic changes [24]. In terms of risk prevention, blockchain could be adopted to help reduce inefficiencies in capacity reservations, mitigation inventory, and backup sources (i.e., **M4**).

In the offer area (i.e., value proposition), blockchain makes the manufacturing industry a more transparent, immutable, and honest place (i.e., **M5**) [29]. The computational trust offered by blockchain is a solution to further address sustainability issues in a decentralized manufacturing network (i.e., **M6**). Trust across multiple entities in the manufacturing network is the predominant factor driving the adoption of blockchain. Blockchain uses a decentralized P2P communication mode to efficiently process trading information between entities. Thus, it effectively prevents any single node or transmission channel in the network from being breached by hackers, by causing the whole network to crash and thereby protecting the security of the entire cyber-physical system. Blockchain can also be leveraged to enhance network resilience

Table 1
An overview of metrics for adopting blockchain in the manufacturing sector.

Category	BMC Elements	Metrics of BMC	Notes	Ref.
Infrastructure	Key Resources	**M1:** Greater transparency	Provide improved access, extended visibility, traceability, and disintermediation for key resources	[19, 21, 25, 26]
	Key Activities	**M2:** Decentralized decision	Use shared ledgers that are free from intermediaries	[17]
		M3: More flexibility	Realize more flexible market-oriented collaboration and broader data/ resource sharing	[8, 9, 20]
	Key Partnerships	**M4:** Enhanced risk management	Track the roots and propagation of disruptions	[27, 28]
Offer	Value Proposition	**M5:** Computational trust	Make the manufacturing industry a more immutable and honest place	[7, 29]
		M6: More sustainability	Improve the profitability and competitiveness of manufacturers	[10, 30]
		M7: Higher resilience	Enhance network resilience in times of increased uncertainty	[31]
Customers	Customer Segments	**M8:** Reputation enhancement	Make the organization's data accessible to new participants/ segments, while protecting intellectual property in sharing of product-related information via data provenance	[11, 32, 33]
	Channel	**M9:** Strong coordination	Enhanced coordination and self-organizing capability both upstream and downstream of the manufacturing community	[12]
	Customer Relationships	**M10:** Closer customer relationship	Programmable smart contracts to provide individualized manufacturing services	[34]
Financial Viability	Cost Structure	**M11:** Cost-saving	Reduced costs related to searching, negotiation, transaction, and tracing, and carrying out integration quickly using smart contracts	[35]
	Revenue Streams	**M12:** Extended revenue streams	Collaborative optimization to minimize order delay, damage to products, and multiple data entry	[36]

under increased attacks and risks (i.e., **M7**) [31].

In the customers area (i.e., customer segments, channels, and customer relationships), manufacturers can make the organization's data accessible to new participants/segments to enhance their reputation and thus generate trust (i.e., **M8**) [32]. Manufacturing events can be shared across a community via the immutable blockchain. Other challenges in channel coordination, such as order delay, damage to products, and multiple data entry, can also be minimized by introducing blockchain (i.e., **M9**) [36]. With programmable smart contracts, blockchain can support the operation of diverse individualized manufacturing services (i.e., **M10**) [34]. The smart contracts made in the manufacturing network become transparent and permanently documented for all parties involved.

Regarding financial viability (i.e., revenue streams, cost structure), from the transaction cost theory perspective, blockchain limits opportunistic behavior and environmental and behavioral uncertainty. Based on its transparent nature, blockchain can secure favorable financing terms for manufacturers with lower signaling costs [25]. Also, the cost savings enabled by blockchain ensure the profitability of manufacturers, as well as the sustainability of the whole manufacturing network [30]. Because blockchain is free from intermediaries' interventions, it can prevent contractual disputes in manufacturing service transactions. Manufacturers can significantly reduce costs for managing integration relationships and carry out integration more quickly using smart contracts (i.e., **M11**) [35]. Revenue streams could be extended via collaborative optimization to minimize order delay, damage to products, and multiple data entry with the help of blockchain (i.e., **M12**) [36].

3. Dimensions of blockchain-empowered sustainable manufacturing

As shown in Fig. 1, this paper proposes a two-dimensional framework (i.e., manufacturing system and product lifecycle) for surveying blockchain-empowered sustainable manufacturing.

From the manufacturing system perspective (vertical axis of Fig. 1), blockchain could be designed as an enabler to drive existing manufacturing information systems, such as enterprise resource planning (ERP) and manufacturing execution system (MES), that already exist at manufacturers' workshops. At the workshop level, the blockchain essentially acts as an indexing server to track parts manufacturing and speeds up the automation of manufacturing. At the enterprise level, blockchain enables distributed manufacturers to form a trusted environment and self-organize their interconnection and service transactions through decentralization and transparent credit mechanism. Data can be transmitted between any manufacturer nodes. Order information, transaction history, and other records are logged on the tamper-resistant distributed chain to facilitate safe and convenient product traceability. The planning and scheduling process can be automatically executed via smart contracts to improve efficiency.

In the product management perspective (horizontal axis of Fig. 1), lifecycle activities (including conceptualization, requirement capturing, collaborative designing, process planning, sustainable manufacturing, assembling & inspection, inventory & logistics, delivery & deployment, operation service, and recycling & remanufacturing) are becoming increasingly complex, as more available socialized resources, stakeholders, and sophisticated technologies are involved in the product lifecycle. The exchange and management of product-related information are challenging because of the need for intellectual property protection, security, and trust issues. Blockchain can provide a tool for the product lifecycle management community (including designers, manufacturers, assemblers, and manufacturing service providers) to establish a unified database to share product information and make deals, enabling untrusted manufacturers to exchange capabilities and requirements freely. This metric allows manufacturers to search for a more efficient approach to connect with each other as well as end customers. Decisions at this level of blockchain application are not made by the management board but by a set of consensus algorithms and smart contracts. The deal-making process of product lifecycle management, including initial bidding, the payment process, usage tracking, resource management, and final services, could be automated via smart contracts (e.g., an industrial internet of things [IIoT]-based machine-to-machine payment protocol) and cryptocurrency.

The following two sections study the two dimensions of blockchain implementation in detail.

4. Blockchain-empowered sustainable manufacturing system

Because of the complexity of manufacturing systems, as well as the lack of optimization, the performance of implemented manufacturing systems is much lower than designed, which leads to high carbon emission. Recent advances in edge computing and fog computing provide a new impetus to reconsider blockchain applications in manufacturing systems [37]. Blockchain uses a decentralized P2P communication mode to efficiently process information between machines; thus, it significantly enhances the process flexibility and social sustainability [38]. This section surveys blockchain-empowered architectures and techniques in a sustainable manufacturing system (SMS) according to the International Society of Automation (ISA) 95

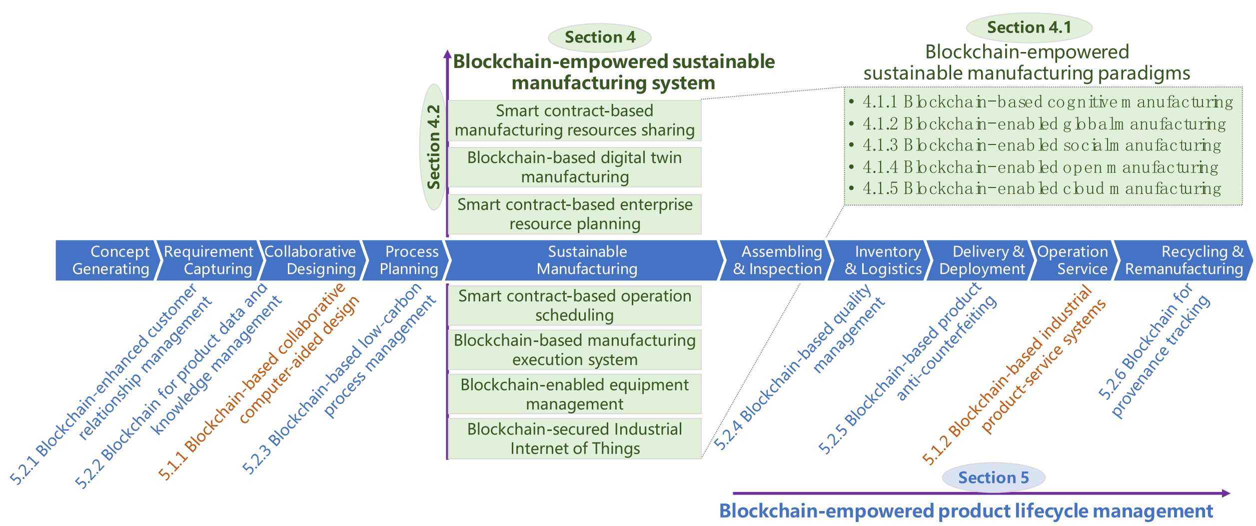

Fig. 1. A bi-dimensional framework for surveying blockchain-empowered sustainable manufacturing.

architecture of a manufacturing system, as shown in Fig. 2.

4.1. Blockchain-empowered manufacturing system architectures

4.1.1. Blockchain-based cognitive manufacturing

Interaction between manufacturers has become a new source of value creation [39]. Cognitive manufacturing has been proposed as an innovative change to Industry 4.0, where artificial intelligence, data analytics, and deep learning technologies are combined for cognitive configuration and operation of logistics, equipment, and quality management. In cognitive manufacturing, the data mining process analyzes the context of equipment operation and worker motion captured by massive sensors [40], making it possible for advanced decision support, including process monitoring, fault diagnosis, and trend prediction. Chung et al. [41] proposed a blockchain-secured cognitive manufacturing architecture. A sidechain-based distributed consensus algorithm was utilized to enhance the fault tolerance capability of smart devices. A Latent Dirichlet Allocation-based topic encapsulation method was used to improve the performance of blockchain to jointly manage manufacturing process information via a P2P distributed ledger. Furthermore, a formatted statistical inference method was designed to mine the decision patterns in the manufacturing process.

Lee et al. [11] proposed a conceptual framework that utilizes blockchain to extend the functionality of a cyber-physical manufacturing system. As shown in Fig. 3, four machines are operated at two geographically separated organizations: 'Organization A' and 'Organization B'. Data captured from machines is uploaded into the fog computing gateways. Meaningful information obtained from the fog layer is gathered into a distributed cloud network for advanced management analytics. Blockchain could significantly improve the quality of the product management by addressing data availability, intelligent prognostics health management, and the predictive maintenance support system.

Blockchain demonstrates the possibility to be a secure infrastructure for enabling machine-to-machine connections and open architecture controls in cognitive manufacturing systems [42]. However, there still are potential limitations and practical challenges, such as colossal information redundancy and low transaction speed, as distributed blockchain nodes need to participate in and record the P2P verification process during transactions.

4.1.2. Blockchain-enabled global manufacturing

The global value chain is increasingly disaggregated with increasingly stringent national laws, hindering manufacturers from building sustainable supply networks. A blockchain is a tool that can take resources and information that was once in the private domain and share them securely. According to the Evidence, Verifiability, and Enforceability framework [43], blockchain could provide more sustainability to manufacturing by making more origin information regarding products available to consumers via smart contracts.

Enabling local manufacturing processes to reduce the impact of the current industrial globalization is crucial, so discovering mechanisms to incentivize, accelerate, and scale this process is fundamental and urgent. This is where blockchain could come in handy, by creating an open platform and decentralized incentivization scheme that can be articulated among multiple stakeholders. In the context of manufacturers sharing idle machining capacities in a dynamic network, Geiger et al. [44] presented a tamper-proof blockchain-based framework for keeping track of distributed operations (including product information and machining parameters) to minimize the cycle time for product manufacturing. Zareiyan and Korjani [45] introduced a blockchain-based decentralized solution named 3D-Chain to provide a global manufacturing ecosystem for manufacturers, designers, and consumers to interact efficiently without any restrictions in the Industry 4.0 revolution. As shown in Fig. 4, 3D-Chain facilitates mass customization and individualization through its network to address the global demand via the following strategies: 1) incentivizing and rewarding beneficial players, 2) developing innovative processes that prioritize global growth in the economy, 3) building software infrastructure for sustainable merging of advanced manufacturing technologies into a new

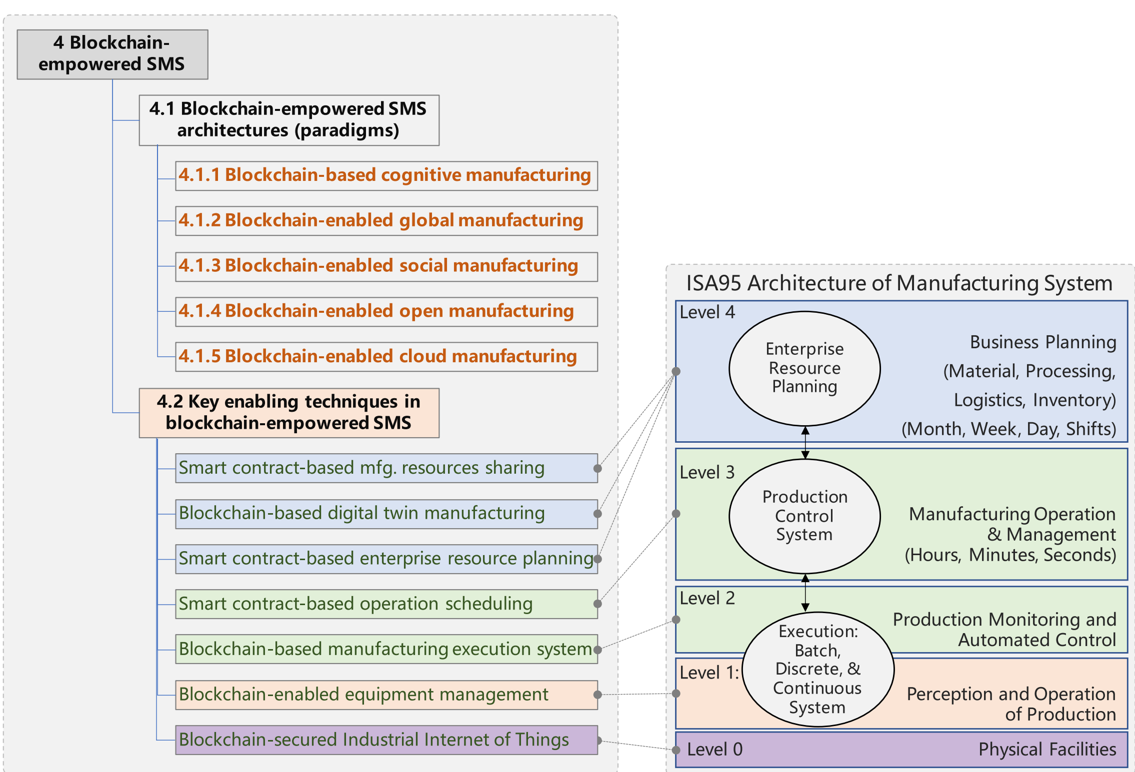

Fig. 2. Major aspects of a blockchain-empowered sustainable manufacturing system.

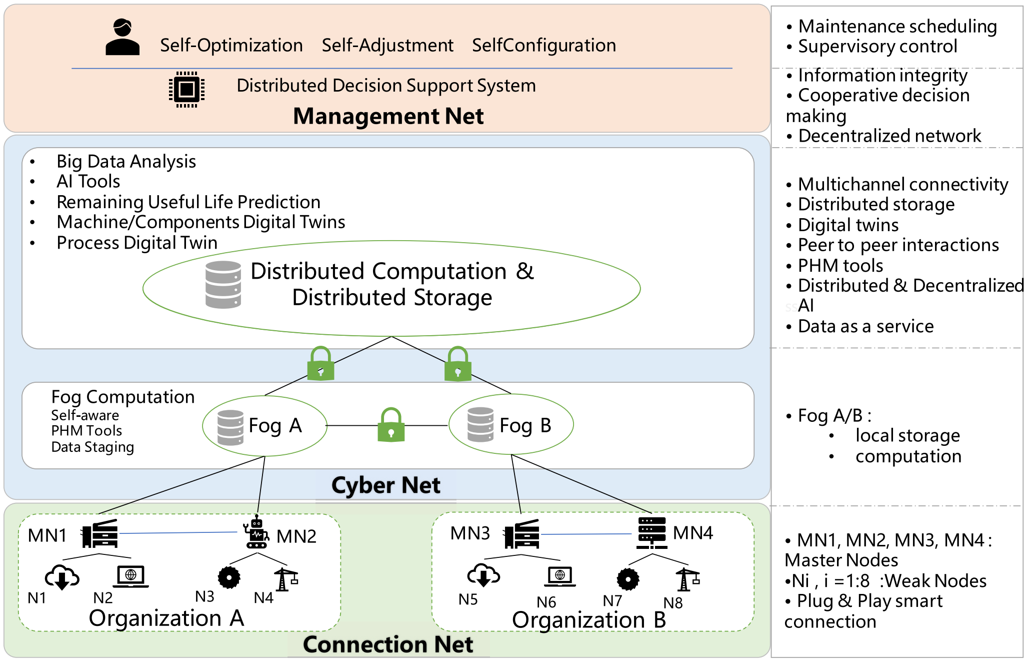

Fig. 3. Blockchain for extending the functionality of managing product operations [11].

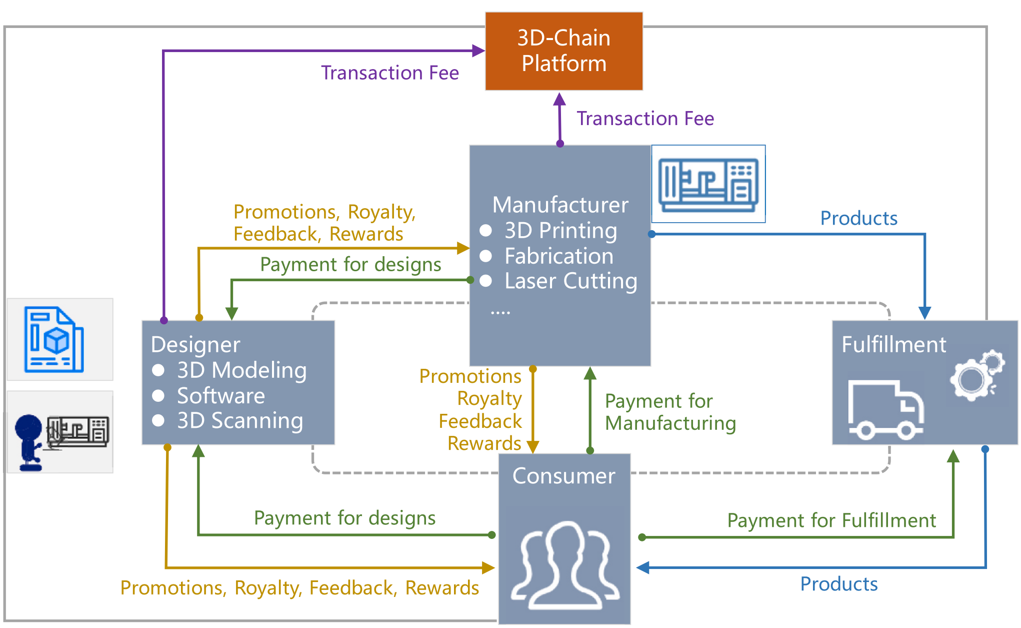

Fig. 4. Workflow of a blockchain-based global manufacturing ecosystem (3D-Chain) [45].

decentralized network, 4) addressing cross-functional components in manufacturing and design of products, 5) decentralizing manufacturing to increase performance and reduce waiting time cost, and 6) continuously evaluating consumers, manufacturers, services providers, and suppliers. However, new personalized manufacturing products are costly and time-consuming. Demands for personalized design are exponentially growing and will soon dominate the manufacturing economy.

Under the global manufacturing paradigm, manufacturers need to be clear about their partners' production capability to make outsourcing decisions. The traditional decision-making method is inefficient because the information asymmetry between manufacturers makes it difficult for managers to obtain accurate decisions. Blockchain contributes to achieving open and decentralized data-sharing mechanisms in a global manufacturing paradigm. Compared with traditional cyber systems, the blockchain-based global manufacturing ecosystem enhances the information interaction capability within the industry alliance. However, the existing blockchain-based global manufacturing system can only accommodate data storage for a limited number of manufacturers, as blockchain requires every node in the system to record encrypted transactions, which is extremely inefficient for mass data growth and analytics [46].

4.1.3. *Blockchain-enabled social manufacturing*

Regarding the increasing production personalization requirements as well as socialized manufacturing resources, the social manufacturing mode has been proposed [2,47].

With product customization, manufacturers share information and collaborate in an inherently trust-less network [48]. Pazaitis et al. [49] envisioned a blockchain-based decentralized cooperation model that can enable the creation of commons-oriented ecosystems in a sharing economy context. Liu et al. [50,51] put forward a blockchain-based production credit mechanism for normalizing and regulating the inter-enterprise collaboration in a social manufacturing paradigm. Angrish et al. [52] designed three smart contract representations to model the relationships among various participants that are formed in a secondary contract index and consistent with the logic of "purchasing-supply" in real-world industrial production activities. All contracts could be derived from the audited smart contract paradigm, which includes three sub-steps: 1) attaching information related to production contracts to the delivery of goods in the form of QR or radio-frequency identification (RFID) codes, 2) using a scanner to scan with the user's private key signature when they sign for it, and 3) completing the payment following the profit distribution in the smart contract. The finished products are directly delivered to consumers by logistics enterprises that are connected to the logistics according to the smart contract paradigm. Finally, customization from production to logistics is completed. Through their smart contract paradigm, the production units of all kinds of production service agencies (i.e., banks, guarantee agencies, and testing agencies) are linked together to provide the corresponding manufacturing services.

In the decentralized cross-enterprise manufacturing network, different smart contract paradigms are urgently needed to cover all the smart contract structures in the entire manufacturing process to meet a variety of value-transfer requirements. The smart contract paradigm of multiple established architectures is provided by the blockchain according to different production modes. A smart contract paradigm is a standard model of smart contracts. Its underlying structure is Turing-complete intelligent implementation of a contract. The standardization of processing is specified in the manufacturing industry, and users only need to describe the contract formation under the contract paradigm, which significantly reduces the implementing complexity. Leng et al. [12] proposed a blockchain-driven Makerchain model to enhance the cyber-credit of social manufacturing among various decentralized makers. As shown in Fig. 5, a digital social manufacturing environment with distributed 3D printers was designed, where all products in the system have a digital twin, and prosumers decide when and where to turn these virtual models into physical products. An anti-counterfeiting method composed of a chemical signature was intended to represent the unique individualized features of products [53].

Once a consumer confirms an individualized product order, all smart contracts from the entire production community are triggered, and commodity prosumers of all components will rapidly self-organize according to the smart contract paradigm. Each production unit is connected to a different community associated with their products by utilizing the existing smart contract paradigm. Through various smart contract paradigms, a digital twin for product manufacturing activities is built in the virtual world. Through the smart contract paradigm, these digital twins enable the creation of more varieties of small-batch fragmentation requirements, which in turn drive the development of new individualized products. The final payment term for the production contract is the logistics delivery. In terms of the smart contract for product logistics, using an electronic signature to sign for the logistics system further enhances the validity of delivery. Generally, the smart contract could mediate the service relationships and enable interaction within the decentralized manufacturing network.

4.1.4. *Blockchain-enabled open manufacturing*

In addition to the well-known shared economy businesses Airbnb and Uber, the digital economy has many other opportunities to create a myriad of sharing applications. Open business is the ultimate paradigm of social manufacturing vision, and it implies many new opportunities for product innovation to leverage diverse capabilities and resources by coherently integrating external partners into the design and manufacturing processes. Such trends lead to the decentralization of the product fulfillment process. Notably, the open business model offers opportunities for small and medium enterprises to fulfill various customer needs in an innovative crowdsourcing manner. Li et al. [54] proposed a scalable blockchain-based cross-enterprise framework to achieve the secure sharing of manufacturing knowledge and resources in open manufacturing ecosystems, thereby enabling the manufacturer to provide flexible, high-quality, and efficient services.

The underlying challenge for adoption and reversion of the open business strategy is the difficulty in 1) group decision-making in the product manufacturing processes, 2) dynamics analysis of crowdsourcing, and 3) game model and collaboration-negotiation contracting schemes. The decision-making processes must be re-engineered to adapt to the collaborative-crowdsourcing process. Xiong [55] proposed a

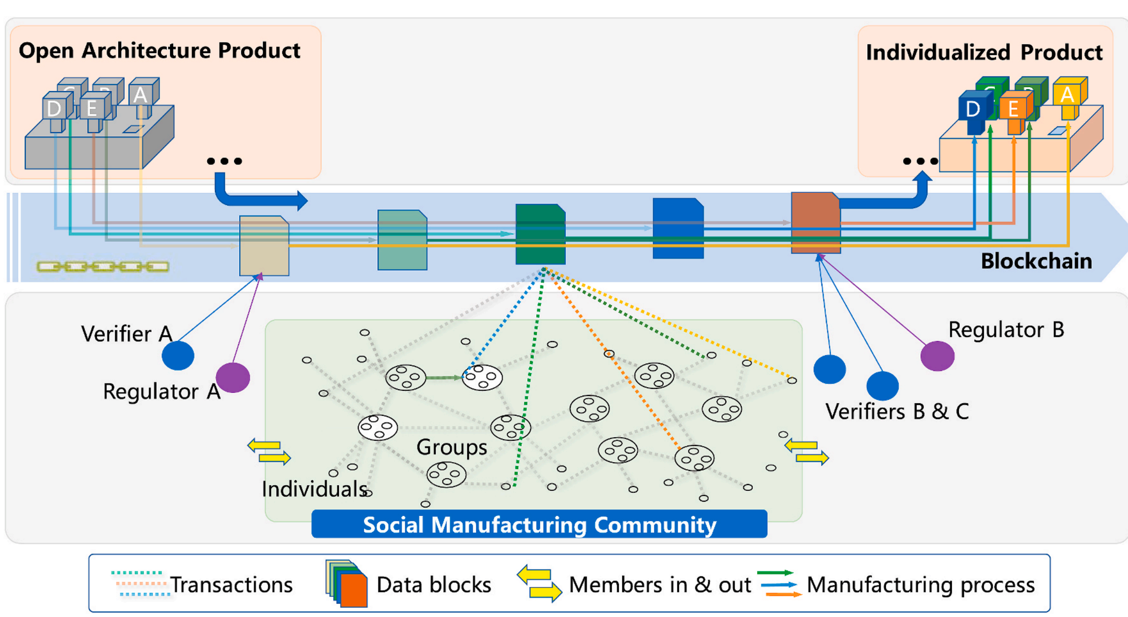

Fig. 5. Blockchain-driven Makerchain for handling the cyber-credit of social manufacturing [12].

collaborative-crowdsourcing product fulfillment model to accommodate the decentralized and collaborative product manufacturing process for open design and manufacturing. To model the dynamics of the partners, an evolutionary competition-cooperation game-theory model was established. The relationships among the participation fraction of the partners, the balance of inter-domain capacity, and income and distribution were determined. The results revealed a competition-cooperation relationship between the external partners and a co-evolutionary characteristic for the entire population.

4.1.5. Blockchain-enabled cloud manufacturing

Cloud manufacturing (CMfg) is a customer-driven manufacturing paradigm inspired by cloud computing. It aims to encapsulate distributed resources as a service and is empowered by the interaction between smart machines for providing manufacturing as a service based on a cyber-physical system. However, the information in cloud manufacturing architecture is typically possessed by a centralized platform. This interaction, based on a centralized structure, provides scope for security and trust issues between the service provider and user [56]. Decentralization may increase operational efficiency. Barenji et al. [57] used two types of blockchain network, i.e., public and private, for manufacturing service providers on CMfg. The public blockchain was used for the service provider level, and the private blockchain was used for the workshop level, which is connected to the machine level for data receiving and gathering. Bahga and Madisetti [58] proposed a blockchain-based CMfg platform to enable peers to deal with each other in a trustless network without a trusted intermediary. The CMfg model interconnects distributed resources to form a pool. However, many manufacturers are unwilling to disclose detailed information about their resources, and this model also lacks sufficient incentive to enable continuous provision of services. Therefore, the operation efficiency and service quality of the entire CMfg community decline [34].

Because centralized resource management and scheduling exhibit low process flexibility, Li et al. [59] proposed a blockchain-based P2P CMfg architecture named BCmfg to improve the scalability of the CMfg platform. Innerbichler and Damjanovic [60] explored the Stellar Consensus Protocol and Federated Byzantine Agreement consensus to ensure data replication quality and computational trust between CMfg instances and manufacturers without a centralized authority. Yu et al. [61] presented a blockchain-based CMfg model to intermediate the quality-of-service-aware service composition and record transaction results to improve system transparency and decentralization. The given model exposes and wraps resources as manufacturing services that can be purchased by consumers.

4.2. An overview of key enabling techniques in blockchain-empowered SMS

Blockchain and smart contracts could be incorporated into various key enabling technologies for manufacturing systems, including the IIoT, manufacturing equipment management, digital twin system, manufacturing execution system, operation scheduling, enterprise resource planning, and manufacturing resource sharing. Table 2 gives a brief review of why and how blockchain and smart contracts could solve different issues.

The IIoT involves the interconnection of things to collect in-situ data and make effective decisions. The traditional centralized IIoT architecture is sensitive to a single point of failure and malicious attacks. Blockchain enables P2P auditable and transparent transactions to eliminate the security vulnerabilities of traditional IIoT architecture [62] (i.e., metrics **M1** and **M4** in Table 1) and provides IIoT applications with capability to make decentralized decisions free from intermediaries (i.e., **M2**). Higher operational resilience could also be realized in times of increased uncertainty (i.e., **M7**) [63]. Many models of blockchain-secured IIoT have been proposed, including a directed-acyclic-graph-structured blockchain system [64], a multi-center decentralized blockchain-based security model [65], blockchain-based distributed key management architecture [66], and permissioned blockchain-based consensus protocol for software-defined IIoT [67]. However, these industrial blockchain solutions for IIoT usually concentrate on realizing large-scale state synchronization, rather than on the optimization mechanism of the self-configuration architecture.

Table 2
An overview of blockchain-empowered architectures for various sustainable manufacturing models.

Models	Notes	Metrics	Ref.
Blockchain-secured Industrial Internet of Things	Enable P2P auditable and transparent transactions to eliminate the security vulnerabilities of traditional IIoT	M1, M2, M4, M7	[62–67, 80]
Blockchain-enabled equipment management	Incorporate blockchain to capture the carbon footprint and enhance trust among different roles in the management of equipment	M4, M5, M8	[68, 81–85]
Blockchain-based manufacturing digital twin	Introduce blockchain to secure the control and exchange of consumable resources	M1, M10	[11,21, 70]
Blockchain-based manufacturing execution system	Enable distributed computing on edge devices to synchronize and aggregate their locally scoped state information on a global scope	M2, M6, M7	[71–75]
Smart contract-based operation scheduling	Build a smart contract-enabled multi-agent model to exchange knowledge and negotiate with each other to achieve a specific goal	M2, M3, M11	[76,77, 86,87]
Smart contract-based enterprise resource planning	Provide immutable shared ledgers across departments and methods of reaching planning consensus	M8, M9, M12	[78,79, 88–91]
Smart contract-based manufacturing resources sharing	Enable machine nodes with the capacity for automated computing transparency regarding an organization's capacity for resources sharing	M10, M11	[22,56, 92–95]

Manufacturing equipment management involves multiple roles, including users, regulators, third-party repair partners, and suppliers; it is essential to determine whether the collected data is valid or accurate. Incorporating blockchain into IIoT solutions could help to predict and prevent failures in manufacturing equipment (i.e., **M4**). Each piece of equipment needs to authenticate each other as well as to ensure the integrity of their exchanged data regarding potential malicious users and use (i.e., **M5**). Blockchain can be used to capture the activities of the product manufacturing process and enhance the reputations among different roles in manufacturing asset management (i.e., **M8**). Third-party repair partners can check the blockchain to determine when to conduct preventive maintenance [68].

One bottleneck for achieving sustainable manufacturing is ensuring interoperability between physical and digital production space. As shown in Fig. 6, in the cyber-physical system (CPS) vision, based on the massive sensors and controllers deployed with each piece of equipment, the IIoT bridges cyberspace with the physical manufacturing system. Cyberspace contains multiple digital twins (e.g., digital twin 2: Manufacturing Execution System [MES] for production management, and digital twin 4: Blockchain system for securing data). Digital twins allow not only visualizing the current status of the equipment, but also predicting its trend by analyzing the manufacturing context via the learned operating behavior patterns [69]. Each digital twin has a specific advantage in manufacturing management. For instance, the Blockchain System (a digital twin) could act as an anti-counterfeiting indexing server to ensure that the production instructions have not

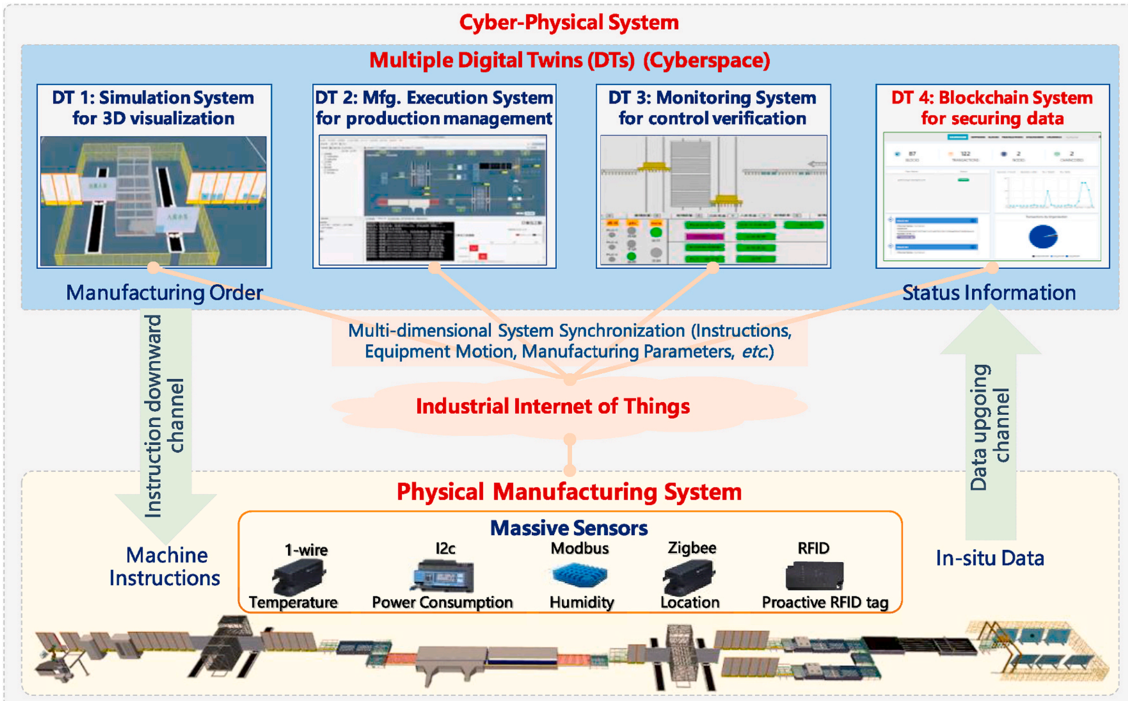

Fig. 6. Illustration of blockchain as one of the digital twins for securing system operation.

been tampered with, while the MES (another digital twin) is efficient for executing and managing upper-level planning. The synchronization of digital twins via the digital thread and cloud platforms suffers from trust problems [21], and one solution is introducing blockchain to secure the control and exchange of consumables (i.e., **M1**) [70]. Each digital twin of manufacturing equipment could be directly operated by the programmable smart contracts as a kind of digital asset to provide individualized manufacturing services (i.e., **M10**).

The function of the MES involves detailed orchestration of the manufacturing processes close to edge equipment in a timely structure. The smart contract-enabled computing service on distributed edge equipment can synchronize its status and broadcast local information to a holistic range (i.e., **M2**). Many scholars have proposed solutions on blockchain-secured manufacturing execution systems, including Stanciu [71], Meyer et al. [72], Raschendorfer et al. [73], Bose et al. [74], and Adhikari and Winslett [75]. In these blockchain-secured MES solutions, computing algorithms deployed in edge devices can reduce bottlenecks to achieve improved sustainability (i.e., **M6**) and enhance network resilience in times of increased uncertainty (i.e., **M7**). However, more conflicts may occur because local execution that is distributed across the manufacturing systems must obey the holistic decisions. A bi-level intelligence model that coordinates upper-level global optimization and lower-level self-organization may be a solution [21].

Operation scheduling in a sustainable manufacturing system is a very complex task because data are collected from multiple sources, such as the manufacturing execution system and enterprise resource planning system. The scheduling decisions are made in the real-time context of multiple phases of the production process. A proactive operation scheduling based on a smart contract is more flexible and efficient with respect to the optimization of the processes (i.e., **M3**), and smart contract-based operation scheduling also results in a decrease in manufacturing costs associated with searching, negotiation, transaction, and tracing (i.e., **M11**) [76]. A set of smart contract-embedded multi-agent models can interact and negotiate with each other to exchange information and thus cooperate on a specific task in a decentralized and open context (i.e., **M2**) [77].

Enterprise resource planning (i.e., ERP) provides details regarding sales, procurement, demand, supply, manufacturing, outsourcing, and logistics [78]. Blockchain-empowered ERP allows channel/net settlement across departments of manufacturers and reduces costs associated with obeying obligations (i.e., **M12**) [79]. Smart contract-based payment and asset pledging could be developed and deployed both upstream and downstream of the manufacturing community with trusted immutable ledgers, integrated with varying self-organizing algorithms for obtaining enhanced planning coordination (i.e., **M9**). Blockchain-empowered ERP could make the manufacturers' data provenance accessible to other participants and thus enhance reputation (i.e., **M8**). The advantages of blockchain lie in providing high-quality and validated historical planning data for mining analytics.

The explosive growth of large-scale personalized product demands requires massive manufacturing resources to quickly self-organize clusters with group intelligence to transform the requirements into real entities. With the help of a vast distributed manufacturing network and other social resources, prosumers can more accurately participate in product design and manufacturing processes to continuously improve products and to extend innovation boundaries (i.e., **M10**) [56]. The trust tax imposed on manufacturers in mutual collaborations is very high [92]. By driving automated paperless appointments between participants via smart contracts, a network of manufacturers can be enabled for automating the integration with computation capability (i.e., **M11**). Although blockchain could be used to help build trustworthy collaborations between manufacturers, a multi-user satisfied evolution model that allows interest-independent manufacturers to achieve long-term expectations and help them reach a consensus is an urgent need.

5. Blockchain-empowered product lifecycle management

A decentralized network formed by user-generated content enables everyone to have the ability to participate in the entire lifecycle of products, which subverts the traditional manufacturing model. The new model gradually shifts the emphasis on product design and manufacturing from producers to consumers. Additionally, with the help of a vast distributed manufacturing network and other social resources, prosumers (a dual role of provider and consumer) can more accurately participate in product design, manufacturing processes, and low-carbon activities to extend the innovation boundary and to continuously save energy. This section surveys blockchain-empowered architectures and techniques in product lifecycle management (PLM), as shown in Fig. 7.

5.1. Blockchain-empowered product lifecycle management architectures

In addition to the manufacturing sector, the design and operation of products are the other two stages in product lifecycle management that involve intensive interactions and collaborations among prosumers. In the product design stage, computer-aided design tools often suffer from an intellectual property protection issue. In the product operation stage, the product-service systems call for secure data transactions across providers and consumers.

5.1.1. Blockchain-based collaborative computer-aided design

Computer-aided design (CAD) is the use of a computer to support the creating, modifying, analyzing, or optimizing of a model. CAD software can provide unified/standardized modeling, improve the productivity of designers, ensure the quality of design, and guide process planning. Distributed and collaborative CAD environments have gained wide popularity in product data management, product lifecycle management, and manufacturing system design [96,97]. One key issue in collaborative CAD environments is data integrity and confidence in information. Blockchain could be the solution to support a trusted authority for the data integrity issue in collaborative CAD environments [98]. Comuzzi et al. [99] presented a blockchain-based reengineering system that constructs the design space bottom-up by analyzing existing design use cases and best-practice experiences. The smart contract could be utilized to automate the alert design and maintenance services in the product lifecycles [100]. In blockchain-based CAD solutions, a significant challenge is how to process and broadcast heterogeneous multi-source data from various stakeholders to the blockchain network.

5.1.2. Blockchain-based industrial product-service systems

With the growth of product complexity, there has been increasing demand in the global maintenance service domain across the world. With thousands of spare parts and hundreds of customers distributed globally, a manufacturer needs to manage a massive amount of data. Industrial product-service systems (IPSS) offer the integration of product, service, infrastructure, and network to jointly satisfy a user's requirements and preferences, as opposed to the traditional focus on outcomes. Adopting IPSS is recognized as a manufacturer's environmental improvement strategy toward self-learning growth and higher profits than with products alone. A product lifecycle is composed of an event chain consisting of the manufacturing process and product service. Huang et al. [101] introduced blockchain to create a database of all service transactions and integrated a smart contract for responsive action in the context of IPSS. Managing sustainability is critical for IPSS at both global and local levels. Blockchain supports increased visibility of carbon footprints in a supply chain [102]. Fu et al. [103] proposed a blockchain-based emission trading scheme framework to expose carbon emission to the public and establish a feature to reduce emissions for all critical steps of clothing making for the fashion apparel manufacturing industry. Blockchain holds promise for addressing challenges in product lifecycle tracing associated with the triggering and delivery of service in the context of IPSS.

Blockchain enables managers to build complex models of a manufacturing network using a data-driven approach and provide multiple services and products faster with improved reliabilities to serve consumers better than their competitors. Based on timely information sharing across organizations globally via blockchain, repair partners and regulators could monitor the dynamic updating of information for maintenance to minimize downtime and to record the work for future optimization [104]. As manufacturing, operations, and maintenance become increasingly involved in the aviation and space sectors, a digital transformation in the aviation domain across the world is underway with respect to blockchain. Airbus uses blockchain and RFID to track parts for maximizing operational efficiency/performance, faster

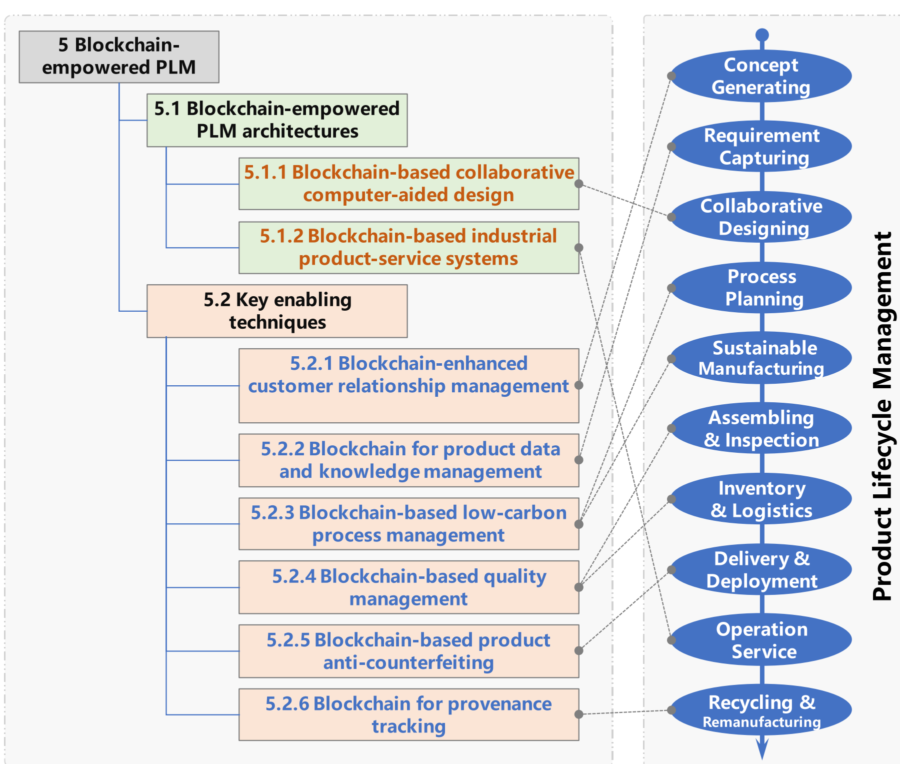

Fig. 7. Major aspects of blockchain-empowered product lifecycle management.

delivery, and reduced error/cost. Each part is manufactured and assembled with a pre-specified life expectancy and specific requirements for maintenance. Madhwal and Panfilov [105] proposed a blockchain-empowered decentralized system both for assisting in maintaining an inventory of aircraft segments and monitoring the operational performance and usage. The proposed method could build a transparent supply network of aircraft parts and help managers analyze the source of availability of parts to reduce the risk of counterfeiting. However, the use of blockchain has shortcomings, such as irreversible contracts and reduced competition; thus, further research needs to be conducted to unlock the full potential of blockchain-based IPSS.

5.2. Key enabling techniques

A blockchain is a new approach to extending the functionality of conventional product data management systems under a distributed environment. Many key enabling technologies have been proposed in different phases of product lifecycle management (listed in Fig. 7). This section surveys blockchain-empowered techniques in product lifecycle management.

5.2.1. Blockchain-enhanced customer relationship management

Increasing globalization, e-commerce usage, and social awareness are leading to increased consumer requirements for variety, value, and convenient product services. Fulfilling the increased complexity of consumer requirements has required manufacturers and service providers to evolve into networks with numerous flow paths in manufacturing involving many organizational handoffs, to effectively manage a large number of complex products/services with shorter lifecycles and high transaction volumes [106]. Blockchain makes it possible for customers, manufacturers, and product service providers to make a deal and provide services in a verifiable and low-carbon manner, as manufacturers and product service providers endeavor to develop smart service contracts for the transaction flow via machine-to-machine interaction mechanisms. The blockchain could record the feedback data of product service from users, verify the authenticity, and securely share it with product manufacturers and service providers to improve the service offering [107].

Bulbul and Ince [108] presented a blockchain-enabled promotion asset exchange model for gathering more detailed information from manufacturers to solve usability bottlenecks in conventional customer loyalty programs. The smart contract and token mechanism were incorporated into the promotion asset exchange model to digitalize transaction processes and thus improve the usability for users. Considering the opaque product distribution and low distribution margin, Yoo and Won [109] proposed a smart contract system for the price-tracking portion of customer relationship management, which could make the product distribution more transparent and thereby discourage manufacturers from chasing exorbitant profits. Narayanaswami et al. [110] proposed a blockchain-based reference software architecture to provide visibility, document provenance, and allow permissioned data access to facilitate the automation of many high-volume tasks in modern supply chains, such as reconciliations, payments, and settlements. Lee et al. [111] proposed a blockchain-based reputation management method and trustless P2P service architecture that enables service vendors to transfer the security and maintenance responsibility to consumers and thus increase the reliability and accuracy of each individualized manufacturing and product service. The reputation management depends on dynamic feedback to guide the consumer's immediate decisions with a classified mechanism. Leng et al. [12] proposed a decentralized blockchain-driven Makerchain model to enhance the cyber-credit among manufacturing service providers and demanders. A tree model of smart contracts was presented as the bridge between service demanders and service providers (Fig. 8). Various smart contracts for the individualized product can be inherited from the corresponding reference contract while customizing formalized parameters, generation rules, and initiation mechanisms. Once a personalized product order is confirmed, manufacturing services are triggered and self-organized according to the reference contract tree.

High-quality data are of great significance for managing the

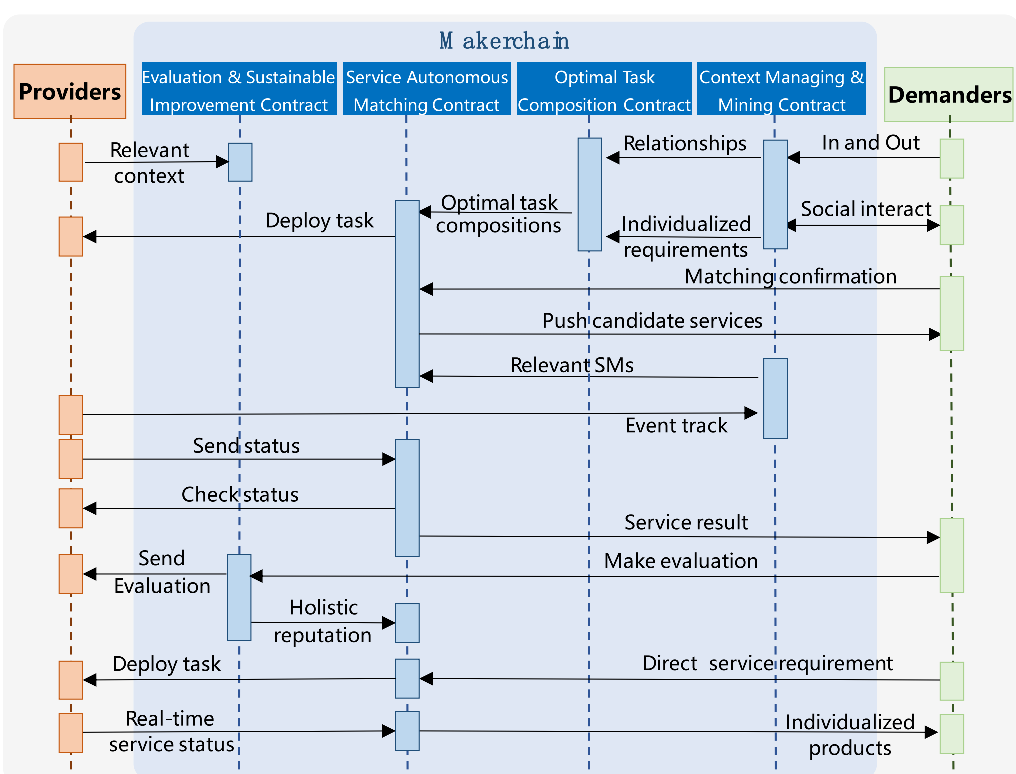

Fig. 8. Interaction flow among smart contract tree and smart entities in the Makerchain [12].

customer relationship accurately and precisely. As a result, manufacturers are collecting massive volumes of personal consumer data while ignoring privacy concerns. Although manufacturers attempt to satisfy these privacy-preserving needs with some risk reduction tools, they still cannot assure cryptographic security. A secure multiparty computation system [112] that allows a manufacturer to collaborate with partners without disclosing their data is an urgent need. If the privacy protection issue is solved, a higher portion of product data sharing and a decrease in fraud/misuse can be expected.

5.2.2. Blockchain for product data and knowledge management

A critical factor in Industry 4.0 is a consistent data flow along the product manufacturing chain. Managing the exponentially increasing quantity of manufacturing data is vital to support new requirements for daily operations and requires access to reliable data. The strategies to achieve data vary from a centralized database to distributed systems and cloud computing. While a centralized database could be corrupted or tampered with, a distributed database suffers from synchronization efficiency issues. Blockchain has a native synchronization-discrepancy-resistance mechanism. Papakostas et al. [113] proposed a conceptual blockchain application for managing product information in the development processes. Fig. 9 shows an example of implementing seven transactions input to the blockchain operated among an original equipment manufacturer (OEM), an engineering service provider, two additive manufacturing service providers, and a recycler. The system is verified in a networked multi-node context, where participants interact with the blockchain agents in a variety of transactions. The metrics of the proposed system for product lifecycle management include a cost-efficient and affordable data exchange mechanism among partners, greater transparency for all transactions, improved traceability of operations, and higher accountability for all networked participants.

Knowledge asymmetry in a distributed manufacturing network is a critical issue. Blockchain creates possibilities for manufacturers to share value and knowledge in a decentralized environment [114]. Adhikari and Winslett [115] proposed a hybrid secure information architecture that integrates blockchain computing and cloud storage to manage data. Li et al. [116] proposed a mold design knowledge sharing platform via integrating a private cloud with blockchain. The private cloud is used for storing the mold redesign knowledge for each manufacturer privately, while blockchain is introduced to record knowledge transactions securely. Zhang et al. [117] proposed a decentralized knowledge sharing framework integrating blockchain with edge computing. Blockchain guarantees the tamper-proofing of knowledge sharing, while edge computing provides smart services to fulfill the decentralization requirements. Manufacturers can use the shared knowledge on a blockchain platform to identify which products contain parts that share less value to achieve a circular economy. In the end-of-life stage of products, manufacturers can gather accurate information from the blockchain to improve their ability to design by-products from their end-of-life products [118]. Those end-of-life products with higher resource usages and lower circularity potentials can be considered for removal from a product portfolio to improve the operational durability of products and maximize supply chain value. Blockchain can also contribute transparency and security to rational product deletion [119]. As shown in Fig. 10, blockchain-enabled strategic product deletion management is a multi-phase process (e.g., recognition, analyzing and revitalization, evaluation and decision formatting, and implementing in product management) that requires decision-support information from supply activities.

The social informatics that involves technology, people, organizations, and their activities are critical for enabling experience-based knowledge [120]. Including all original raw data in the blockchain

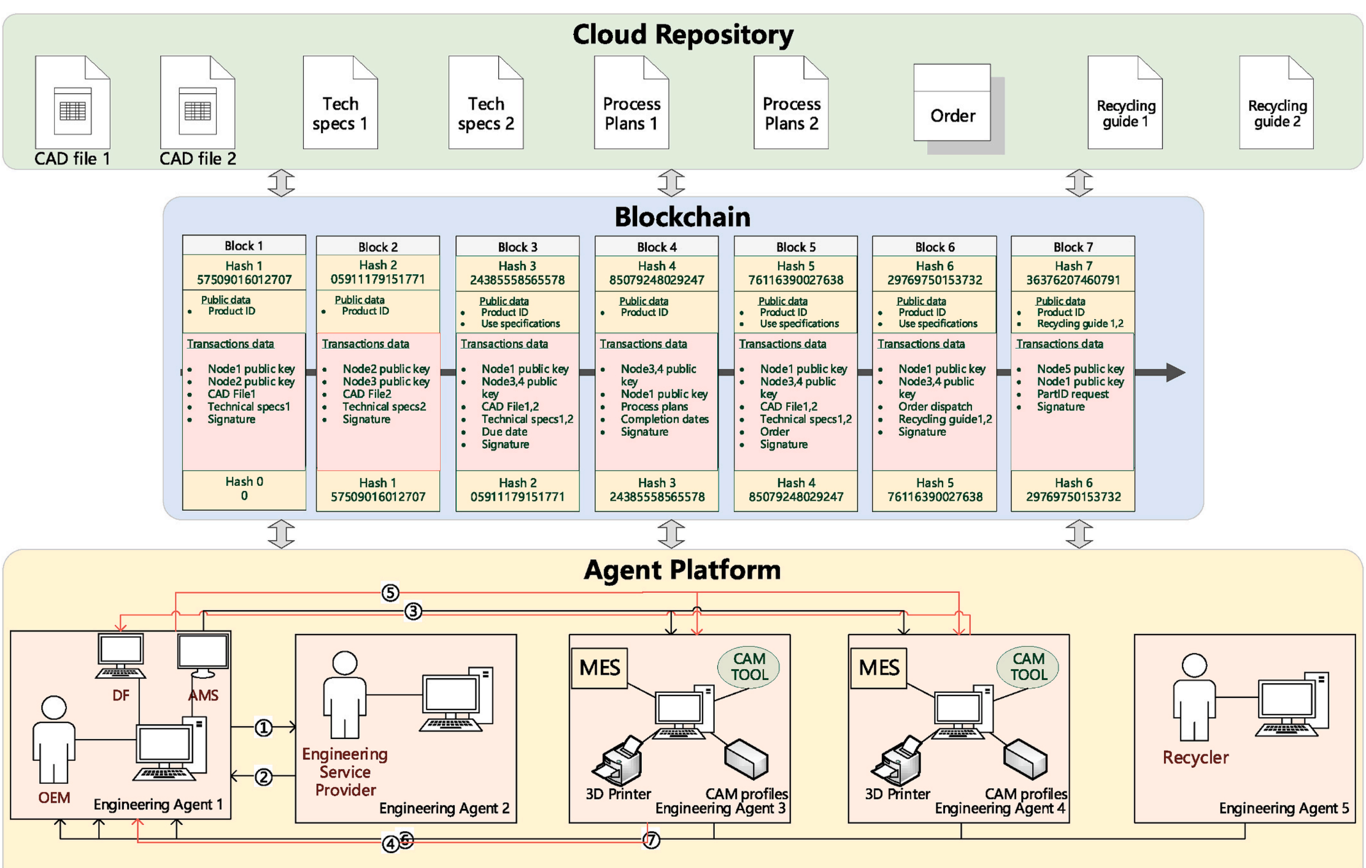

Fig. 9. Managing the product development process utilizing blockchain [113].

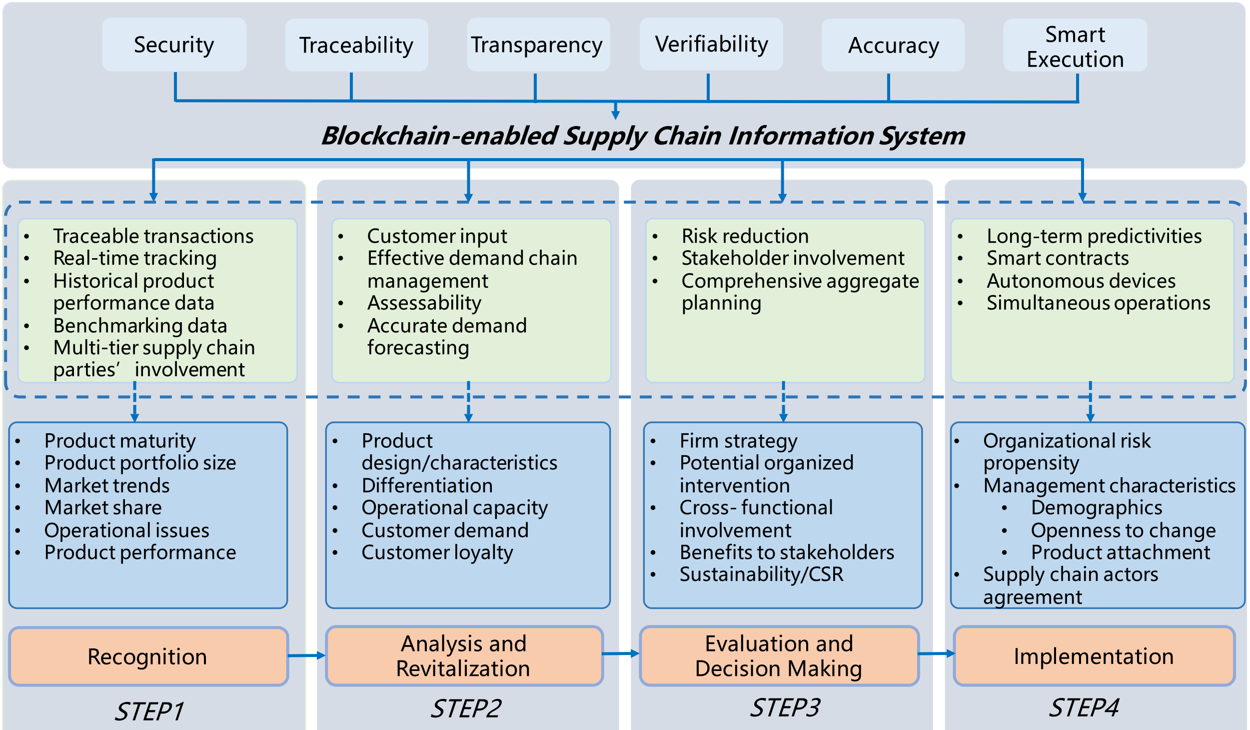

Fig. 10. Blockchain-enabled strategic product deletion and supply chain information management [119].

prevents consuming too much data and reducing performance. Instead, the hash of manufacturing data is supposed to be stored in the blockchain, which means that the portal requires a separate system to store the actual manufacturing data. Conversely, the prevention of intellectual property theft is a crucial technology for enabling knowledge sharing [121].

5.2.3. *Blockchain-based low-carbon process management*

Decentralized decision making is a fundamental concept in Industry 4.0 [122]. Business process management (BPM) systems in Industry 4.0 are required to digitize, automate, and optimize process workflows and enable the transparent interoperations of manufacturing and product service providers to achieve higher system efficiency, including higher profits, quicker responses, and better service quality. Ciccio et al. [123] investigated the manner in which a business process on a blockchain infrastructure should be run to provide traceability of its run-time enactment from the transactions written on-chain. Viriyasitavat et al. [124] proposed a blockchain-based automated BPM solution to transfer and verify the trustworthiness of business partners. As shown in Fig. 11, the services are selected and composed in an open business environment provided by the blockchain, and an energy-saving and cost-effective moving of quality of services is enabled in the workflow composition and management.

When large-scale distributed industrial plants measure the data from a shared common source to offer interactive services without outside interference, trustworthiness and immutability must be guaranteed among them. Wang et al. [125] proposed a hierarchical and scalable blockchain-based secure metering system, named SMChain, to provide reliable security, guaranteed trustworthiness, and immutable services. Sharma et al. [126] integrated a miner node selection algorithm into a

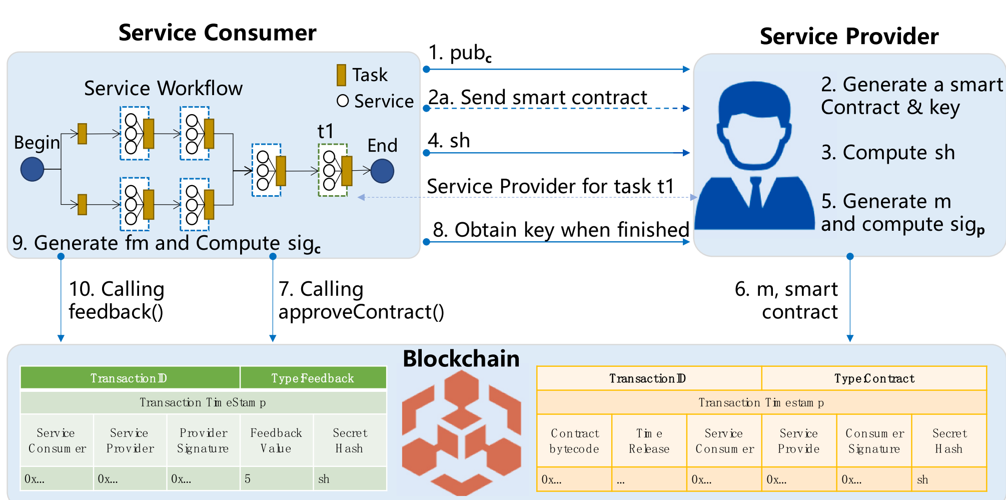

Fig. 11. Workflow of a blockchain-based automated BPM solution [124].

blockchain-based distributed business framework to provide integrated, personalized, and on-demand automotive services. Rožman et al. [127] used blockchain for writing down agreements, making transactions, and obtaining trustworthy listing of public logistics services and information on a logistic chain.

Blockchain opens up new opportunities for BPM by enabling transactions to be automatically executed and recorded by smart contracts in a decentralized architecture and without the intervention of central authoritative managers in the workflow [128]. However, because blockchain may affect diverse dimensions of business models in different industries, managers should follow developments in this field to prepare for possible disruptions in their industries [129].

5.2.4. Blockchain-based quality management

Quality management in a distributed manufacturing context still has difficulties arising from a lack of trust, the self-interest of manufacturers, asymmetry in processing information, and the absence of quality inspections. The primary reason is a lack of transparency, which forces manufacturers to conduct quality control locally based on localized data. Blockchain is a potential method to solve these issues. Chen et al. [130] proposed a blockchain-based quality management framework for the supply chain. ElMessiry and ElMessiry [131] proposed a blockchain-based textile quality improvement framework for identifying quality-defective batches in a manufacturing network. Because of the multi-stage manufacturing processes that the products go through and the large volume of context data involved, cross-stream troubleshooting is difficult because it is difficult to locate the source of quality issues. It is challenging to directly trace defects back to when the defective batches entered and circulated along the way in the network, resulting in wasting resources and frustrating downstream manufacturers. From the perspective of customers, it is difficult for them to detect quality issues in the products they purchased. To protect customers from various malicious exploitations, manufacturers have attempted to build centralized certification systems. However, certification systems are costly, and their implementation may be unsecure. Marfia and Esposti [132] proposed a blockchain-based integrated approach to enhance the trust of product quality and gain more product/service value. Actually, in blockchain-based quality management solutions, smart contracts could be integrated with automated quality control programs such as statistical process control (SPC).

5.2.5. Blockchain-based product anti-counterfeiting

Because reverse engineering continues to receive traction in various sectors, the issue of preventing product counterfeiting has consequently increased [33], and it is difficult to validate the lifecycle activities of products efficiently while assuring anti-counterfeiting capabilities. Counterfeiting constitutes a significant challenge in current manufacturing networks. Many chemical methods and physical methods have been proposed to prevent copying in product manufacturing.

Tamper-proof blockchain, in combination with chemical/physical methods, offers a promising solution for product anti-counterfeiting. The basic idea is to identify each product with a one-to-one counterfeit-proof feature and to then track it using a distributed system based on a blockchain. The changes in part ownership are recorded and termed a chain of custody. Kennedy et al. [33] presented a low-cost anticounterfeiting method for 3D-printed parts that is accomplished using blockchain, where inclusion of a chemical signature profile consisting of measured fluorescence emission data of embedded nanomaterials is provided to the digital twin to improve part security. Alzahrani et al. [133] proposed a decentralized block-supply chain to detect counterfeiting by integrating blockchain with near field communication (NFC). Lu et al. [134] proposed a distributed and append-only counterfeiting prevention blockchain jointly governed by multi-parties themselves via a consensus algorithm to mitigate counterfeiting in automotive manufacturing. Generally, chemical processes may be cumbersome and time-consuming, while physical techniques such as RFID tags can be cloned.

Counterfeit drugs are a prominent issue resulting from the lack of traceability of the supply within the pharmaceutical industry [135]. Tseng et al. [136] proposed Gcoin blockchain to enable transparent transactions in drug manufacturing and supply. Wu and Lin [137] presented a blockchain-based pharmaceutical recall service system for preventing low efficiency and data tampering, thus enhancing network transparency. Steinwandter and Herwig [138] implemented a new smart contract built on top of the Ethereum blockchain for data integrity in a pharmaceutical context. Sylim et al. [139] developed a distributed application on a smart contract for validating every transaction of pharmacy surveillance, which can help end customers check the drug manufacturing and distribution history by scanning a printed QR code. Vruddhula [140] combined cryptographical micro QR signed/printed directly onto drugs by the manufacturer with transactions in a decentralized blockchain for drug anti-counterfeiting. Holland et al. [141] incorporated digital rights management into an additive manufacturing platform to prevent intellectual property theft. Mandolla et al. [142] incorporated a digital twin into blockchain for the metal additive manufacturing process in the aircraft sector to secure and organize the process data. Yampolskiy et al. [143] provided a comprehensive, structured survey of state-of-the-art as well as attack taxonomies. While the blockchain is robust for passively accounting for a product's chain of custody, a process for physical/chemical verification of a product/part is required, as one could still craft a fake digital twin when the private key of the user is compromised. Moreover, there exist significant challenges regarding the scalability and throughput of blockchain-based product anti-counterfeiting [144].

The distributed nature of the blockchain also brings concerns about privacy protection for protecting businesses. Blockchain can be more effective than a pricing strategy in terms of eliminating post-purchase regret and improving social welfare. However, blockchain should be adopted only when customers and manufacturers have intermediate distrust regarding products. In markets with relaxed intellectual property regulations against counterfeiting, pricing strategy is more effective than blockchain [145].

5.2.6. Blockchain for provenance tracking

Increasing consumer/government awareness and manufacturers' quality-control goals results in the need to determine the provenance of products. Determining provenance is difficult and costly to maintain with current products that are manufactured under the risks of error/fraud in complex and inter-organizational contexts. Existing centralized solutions suffer from an absence of trust when multiple parties are involved. Blockchain-based models hold promise for better product provenance tracking by forming a digital twin of physical products to help trace activities as well as carbon footprints across numerous manufacturers. The relationship between parts and products is a key factor determining the capability of tracking the provenance of products. Westerkamp et al. [146] proposed a blockchain-based traceability system using smart contracts, in which manufacturers could define the components of the product in the form of recipes. Each part of the recipe is identified as a token corresponding to a batch of products. When the recipe is implemented, a new token is initialized. This model enables the traceability of the products' transformation process.

The idea of industrial blockchain applications for provenance tracing is to provide better visibility and greater efficiency by creating records in the network [27]. Kim and Laskowski [147] coded the provenance trace functions into a smart contract that enforces the traceability constraints on a public blockchain network. Mondragon et al. [148] adopted blockchain for tamper-proofing product provenance in manufacturing, logistics, and inventory processes from composite materials/structures to semi-finished products that require temperature-controlled transportation and storage conditions. Islam et al. [149] presented a blockchain-based traceability scheme for verifying the provenance of integrated circuits. Mondragon et al. [150] used blockchain in the manufacturing of composite materials to enable the certification of carbon fiber-based components of aerospace equipment. Blockchain may bring transparency of product lifecycle management to a new level. Francisco et al. [151] introduced the unified theory of acceptance and use of technology as a tool for tracing supply activities. Agrawal et al. [152] presented a blockchain-based traceability model for the textile and clothing industry. Conventional systems are limited to tracing product logistics rather than manufacturing processes. Westerkamp et al. [153] proposed a non-fungible digital token system based on blockchain for locating each batch of products, including their components. Xu et al. [154] demonstrated a blockchain-based traceability system, called originChain, which restructures the existing software by replacing the centralized database with blockchain to provide transparent tamper-proofing ability with high availability and smart regulatory-compliance with respect to product provenance tracing. The workflow of originChain [154] among service users, traceability providers, and blockchain administrators is illustrated in Fig. 12. The originChain consists of user interfaces, a management layer, an off-chain data layer, and a blockchain layer. The blockchain is utilized as a software connector that contains both data and business logic.

The disassembly decision at the product end-of-life phase requires instructions such that the component can be recycled or disposed of sustainably. Moreover, many components and parts of the product reaching their end-of-life phase may be reintroduced in the network as counterfeit items. Blockchain could be used to improve the traceability of disassembly and recycle decisions, which would also lead to higher accountability for all partners in a green supply chain [155]. For instance, Xu et al. proposed a blockchain-enabled e-waste (the discarded end-of-life entity of electronic components and systems) handling system for the electronics supply chain [156]. In the proposed system, the electronic recyclers collect and update electronic components with the "end-of-life" status to the blockchain ledger, thus preventing them (e.g., recycled chips) from re-entering the supply chain by marking the stage in the database as "e-waste." A blockchain system integrated with digital tracking sensors provides accurate and tamper-proof data for support decisions in the product end-of-life phase. This makes long-term circular economy planning more effective and provides reliable information regarding recycling and remanufacturing of products [119].

Under the growing environmental awareness and social responsibility, various value-adding take-back strategies focusing on end-of-life high-tech product waste and recovery have been proposed by manufacturers to increase profitability while ensuring the environmental sustainability of products. Trade-in contracts are defined to incentivize consumers to exchange used products for up-to-date products. However, when identifying trade-in margins, it is challenging for manufacturers to reasonably predict the quality of returned products to simultaneously ensure manufacturer profitability and support the sustainable development of customer-oriented supply chain activities. This issue inevitably reveals the need for incorporating blockchain-enabled smart technologies to determine the optimal trade-in-to-upgrade contracts. Blockchain authorization could eliminate consumers' hesitation toward remanufactured products by providing transparent information regarding how products were produced, whether they were sustainably sourced and securely preserved, and even ownership transfers [157]. However, both capturing the transformation of goods in manufacturing processes and identifying micro components (e.g., chips and microprocessors) in the blockchain remains a critical issue. The method of combining hardware with software systems is vital to allow manufacturers to authenticate, trace, and analyze the entire lifecycle of the product.

6. Social barriers and challenges

Blockchain-empowered transformation of the manufacturing paradigm is still in its early stages [158]. Many manufacturers have not advanced their blockchain solutions beyond proofs-of-concept. Moving into a new technology space has always been a dilemma for conservative spaces [159]. Challenges in the areas of techniques, social barriers, standards, and regulations impede progress [160]. Fig. 13 provides an overview of social barriers and the challenges associated with achieving

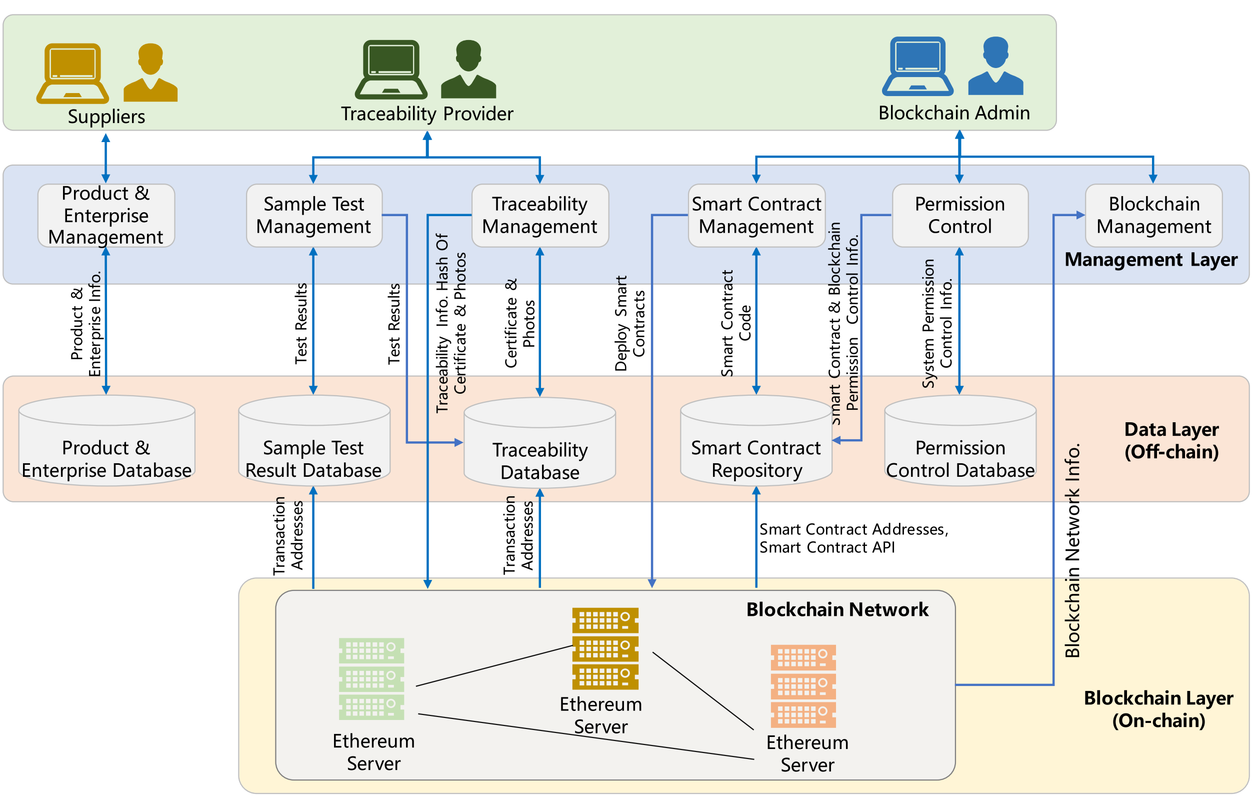

Fig. 12. Workflow of a blockchain-based product provenance tracing system (originChain) [154].

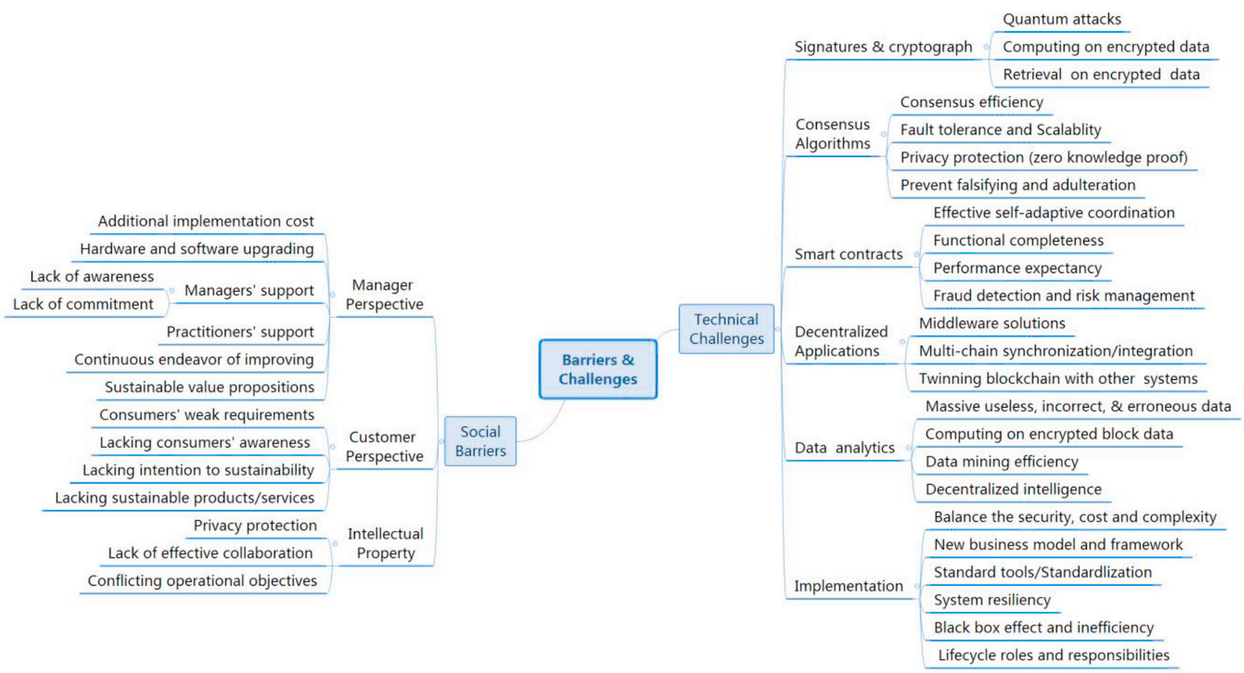

Fig. 13. Social barriers and technical challenges of blockchain-empowered manufacturing applications.

sustainability goals in blockchain-empowered manufacturing applications.

6.1. Social barriers

Because consumers demand that manufacturers disclose information regarding product sustainability, manufacturers should achieve instant traceability in their multilayer global supply chains, in which blockchain offers a promising approach for solving the multilayer complexity and eliminating intermediates from multilayer junctions [161]. However, the implementation of blockchain confronts social barriers with respect to three aspects.

From the manager perspective, although blockchain has the properties of decentralized transparency and auditability that make it ideally suited to socialist paradigms, models, and societies involving public ownership [162], the acceptance of blockchain requires additional implementation costs regarding hardware and software for collecting information as well as automatic execution of smart contracts among participants and organizations. The blockchain-based service network (BSN), which is a blockchain infrastructure where participants can deploy blockchain applications without having to develop a system from the ground up, could be developed to reduce the costs of deploying blockchain-based intelligent applications for manufacturers, compared with building, operating, and maintaining a blockchain system by themselves [163]. Also, upper-level management support is a crucial driver of the successful deployment of sustainable blockchain systems. According to an empirical study in the Indian context, practitioners perceive that blockchain adoption would be helpful for them to pursue maximal benefits and business sustainability [102]. However, decision-makers often do not continuously endeavor to strive to implement new advanced technology, and they stick to sustainable value propositions. Lack of awareness and improving commitment holds back sustainability practices through the manufacturing process and challenges resource allocations decisions. Because no new technology has succeeded with the rip-and-replace method, manufacturers using this blockchain have a more significant impact if it can augment existing technology [164]. Blockchain did not gain a positive public perception in the beginning because of its origin (i.e., cryptocurrencies), so governments may need to formulate policies to encourage or require manufacturers to use blockchain systems to improve their environmental sustainability [165].

From the customer perspective, a factor that can drive innovation in adopting blockchain is consumers' requirements for sustainable and secure products/services. A lack of information regarding consumers' awareness and intention to contribute to sustainable and secure improvement is an obstacle to blockchain applications. Many consumers do not understand the decentralized computing models and have little willingness to participate in paying more for durable and reliable products/services.

From the intellectual property protection perspective, transparency of information in blockchain leads to challenges for various existing privacy policies related to data usage and sharing between partners. The lack of an effective collaboration mechanism among partners with conflicting operational objectives/priorities can prevent the implementation and operation of blockchain to pursue sustainable added-value. Robust rules for information sharing in the blockchain that affect collaboration among partners should be redefined [158].

Generally, major causes, including data safety and decentralization, accessibility, laws and policy, documentation, data management, and quality, should be analyzed to develop a blockchain-empowered sustainable manufacturing strategy [166]. There are two directions for future research concerning social barriers to implementing blockchain. First, the manner in which the blockchain influences social sustainability challenges, and particularly the legal and ethical implications of its implementation, could be explored. Second, a comparison between blockchain enablers and barriers with different manufacturer sizes, for example, in small-medium enterprises and in large corporations, could be studied to provide strategic insights into the implementation dynamics [167].

6.2. Technical challenges

Although researchers aim at achieving global and scalable blockchain-empowered systems in the sustainable manufacturing domain, there are several challenges, such as consensus algorithms and computing paradigms satisfying privacy protection needs in manufacturing systems. The storage scalability problem is a primary problem confronting practitioners when they adopt the blockchain system, in which cloud computing techniques may be integrated. Based on the decentralized information sharing and interconnection context enabled by the blockchain, designing scalable consensus algorithms and smart contracts to assist effective self-adaptive coordination in each sustainable manufacturing systems is challenging. On the premise of meeting the user's individualized requirements for functional completeness and performance expectancy, it is necessary to balance the security, construction costs, and system complexity [168]. In particular, consensus efficiency is one significant difficulty regarding the large-scale application of blockchain [169]. The immutability of information is essential to prevent falsifying and adulteration of data without consensus. Manufacturers still strive to adopt blockchain for recording massive useless, incorrect, and erroneous data, which cannot be deleted. However, the data statistical analysis ability of the existing blockchain applications is weak. Increasing the size and number of data blocks is still a storage dilemma for processing big data in real-time scenarios. Moreover, current blockchain platforms rely on digital signatures and cryptographic hash functions, which are vulnerable to quantum attacks. Realizable and scalable quantum-safe blockchain applications are an urgent need [170].

Although smart contracts are designed to build the linkage mechanism between mass individualization demands [171] and the digital factory, decentralized applications (DApps) are also of great significance for the future value of blockchain [172]. A manufacturer may use a public blockchain network for purchase transactions while executing smart contracts on a permissioned blockchain network for manufacturing operations and planning [173]. Therefore, middleware solutions should be designed to unify and synchronize different blockchain systems and physical systems [174]. Multi-chain synchronization/integration technologies such as side-chains are an urgent need. Also, tokens on blockchains, which can represent a wide range of digital assets and can be transferred without any involvement of centralized entities or borders, could be studied to offer incentives to cooperate and compete to create circular economy ecosystems [175].

The new business model, framework, and standard tools are some of the biggest challenges facing the process of blockchain application. Despite the key strengths of visibility, validation, and resiliency, the corresponding weaknesses of applying blockchain are a lack of privacy and standardization, the black box effect, and inefficiency [176]. Effective adoption of blockchain to transform a current organization into a new decentralized infrastructure faces a range of challenges regarding standards, environmental regulations/rules, and regulatory compatibility to coordinate issues [177]. The lack of consensus concerning definitions, implementation, management, and core attributes is driving the need for standardization [178]. Standardization activity is needed to enable blockchains to be interoperable for use in new roles [179] and responsibilities through which product lifecycle events captured in the blockchain should be reconciled among various participants on the network [180].

Automated product service calls for big data analytics as a prerequisite [181]. Because data are now available on the blockchain with high quality, data analytics can now be encoded into smart contracts running on agents that can make decisions representing the participants [182]. If designed well, decentralized intelligence may lead to sustainable and energy-saving systems [183].

7. Concluding remarks

Sustainable manufacturing is a blueprint in line with the United Nations' Sustainable Development Goals, in the "Responsible consumption and production" and "Industry, innovation and infrastructure" aspects. Promoting new information and communication technology infrastructures, including blockchain and smart contracts, is a crucial driver of economic growth and sustainable development in the manufacturing sector. This paper surveys the landscape of blockchain-empowered sustainable manufacturing in the Industry 4.0 vision. The manufacturing system perspective and the product lifecycle management perspective regarding implementation of blockchain technology in sustainable manufacturing are analyzed. From the manufacturing system perspective, blockchain could be designed as an enabler to drive existing manufacturing information systems, such as ERP and MES, which already exist in manufacturers' workshops. From the product management perspective, blockchain could provide a tool for the product lifecycle management community (including designers, manufacturers, assemblers, and manufacturing service providers) to establish a unified database to share product information and make deals, enabling untrusted manufacturers to exchange capabilities and requirements freely.

The contribution of this survey is twofold. First, for a structured discussion of the metrics associated with adopting blockchain in different situations, twelve evaluation metrics (i.e., M1-M12 in Table 1) for adopting blockchain in the manufacturing sector are defined and organized on the basis of the business model canvas (BMC). The extent to which these blockchain-empowered architectures and key enabling techniques have been addressed in the literature in terms of sustainable manufacturing has been investigated. Second, this survey summarizes challenges regarding techniques, social barriers, standards, and regulations impeding progress. Blockchain-empowered transformation of the sustainable manufacturing paradigm is still in its early stages and must move past the hype phase to prove its sustainability in the mainstream environment. Many manufacturers have not advanced their blockchain solutions beyond proofs-of-concept. This survey provides insights from the analysis of challenges to achieving sustainability and energy-saving goals that can potentially shed new light on addressing urgent industrial energy conservation concerns.

Various advanced sustainable manufacturing modes always coexist, but the blockchain is not suitable for all sustainable manufacturing modes. Before we introduce blockchain into sustainable manufacturing systems, it is necessary to determine what metrics make it unique and what costs are associated with its implementation. Continually monitoring its implementation to ensure that these systems achieve the desired energy-saving and energy-conserving benefits is also critical. We believe that our study is a critical reflection of significant conceptual and technical advances at this junction of dramatic development, and we hope that our effort lays a strong foundation for making blockchain-empowered sustainable manufacturing a new energy conservation field with respect to research and engineering.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the Science and Technology Planning Project of Guangdong Province of China under Grant No. 2019A050503010, 2019B090916002, and 2019A1515011815; the National Key R&D Program of China under Grant No. 2018AAA0101704 and 2019YFB1706200; the National Natural Science Foundation of China under Grant No. 51705091 and No. 71932002; the Shenzhen Special Fund for the Development of Strategic Emerging Industries under Grant No. JCYJ20170818100156260.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2020.110112.

References

[1] Ghobakhloo M. The future of manufacturing industry: a strategic roadmap toward Industry 4.0. J Manuf Technol Manag 2018;29:910–36.
[2] Jiang P, Leng J, Ding K, Gu P, Koren Y. Social Manufacturing as a sustainable paradigm for mass individualization. P I MECH ENG B-J ENG. 2016;230:1961–8.
[3] Kostakis V, Papachristou M. Commons-based peer production and digital fabrication: the case of a RepRap-based, Lego-built 3D printing-milling machine. Telematics Inf 2014;31:434–43.
[4] Wulfsberg JP, Redlich T, Bruhns FL. Open production: scientific foundation for co-creative product realization. Prod Eng Res Dev 2011;5:127–39.
[5] Bonvoisin J, Boujut J. Open design platforms for open source product development: current state and requirements. Proceedings of the 20th international conference on engineering design. Jul. 27-30 2015, Politecnico Di Milano, Italy. p. 11-22.
[6] Moldavska A, Welo T. The concept of sustainable manufacturing and its definitions: a content-analysis based literature review. J Clean Prod 2017;166: 744–55.
[7] Mourtzis D, Doukas M. Decentralized manufacturing systems review: challenges and outlook. Logist Res 2012;5:113–21.
[8] Leng J, Jiang P, Zheng M. Outsourcer–supplier coordination for parts machining outsourcing under social manufacturing. P I MECH ENG B-J ENG. 2017;231: 1078–90.
[9] Leng J, Jiang P, Ding K. Implementing of a three-phase integrated decision support model for parts machining outsourcing. Int J Prod Res 2014;52:3614–36.
[10] Matt DT, Rauch E, Dallasega P. Trends towards distributed manufacturing systems and modern forms for their design. Procedia CIRP 2015;33:185–90.
[11] Lee J, Azamfar M, Singh J. A blockchain enabled Cyber-Physical System architecture for Industry 4.0 manufacturing systems. Manuf Lett 2019;20:34–9.
[12] Leng J, Jiang P, Xu K, Liu Q, Zhao JL, Bian Y, et al. Makerchain: a blockchain with chemical signature for self-organizing process in social manufacturing. J Clean Prod 2019;234:767–78.
[13] Abeyratne SA, Monfared RP. Blockchain ready manufacturing supply chain using distributed ledger. Int J Res Eng Technol 2016;5:1–10.
[14] Queiroz MM, Telles R, Bonilla SH. Blockchain and supply chain management integration: a systematic review of the literature. Supply Chain Manag 2019: 10–1108.
[15] Zhao JL, Fan S, Yan J. Overview of business innovations and research opportunities in blockchain and introduction to the special issue. Financial Innovation 2016;2:1–7.
[16] Al-Jaroodi J, Mohamed N. Blockchain in industries: a survey. IEEE Access 2019;7: 36500–15.
[17] Shah A. The Chain Gang. Mech Eng. 2019:31–5.
[18] Morkunas VJ, Paschen J, Boon E. How blockchain technologies impact your business model. Bus Horiz 2019;62:295–306.
[19] Wang Y, Han JH, Beynon-Davies P. Understanding blockchain technology for future supply chains: a systematic literature review and research agenda. Supply Chain Manag 2019;24:62–84.
[20] Schmidt CG, Wagner SM. Blockchain and supply chain relations: a transaction cost theory perspective. J Purch Supply Manag 2019;25:100552.
[21] Leng J, Yan D, Liu Q, Xu K, Zhao JL, Shi R, et al. ManuChain: combining permissioned blockchain with a holistic optimization model as bi-level intelligence for smart manufacturing. IEEE T Syst Man Cybern -Syst. 2020;50: 182–92.
[22] Leng J, Jiang P. Dynamic scheduling in RFID-driven discrete manufacturing system by using multi-layer network metrics as heuristic information. J Intell Manuf 2019;30:979–94.
[23] Wang C, Jiang P, Ding K. A hybrid-data-on-tag–enabled decentralized control system for flexible smart workpiece manufacturing shop floors. P I MECH ENG C-J MEC. 2017;231:764–82.
[24] Barenji RV, Barenji AV, Hashemipour M. A multi-agent RFID-enabled distributed control system for a flexible manufacturing shop. Int J Adv Manuf Technol 2014; 71:1773–91.
[25] Chod J, Trichakis N, Tsoukalas G, Aspegren H, Weber M. On the financing benefits of supply chain transparency and blockchain adoption. Manag Sci 2019. https://doi.org/10.1287/mnsc.2019.3434.
[26] Kumar NM, Mallick PK. Blockchain technology for security issues and challenges in IoT. Procedia Computer Science 2018;132:1815–23.
[27] Ivanov D, Dolgui A, Sokolov B. The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. Int J Prod Res 2019;57: 829–46.
[28] Sturm LD, Williams CB, Camelio JA, White J, Parker R. Cyber-physical vulnerabilities in additive manufacturing systems: a case study attack on the .STL file with human subjects. J Manuf Syst 2017;44:154–64.
[29] Lee J, Pilkington M. How the blockchain revolution will reshape the consumer electronics industry. IEEE Consum Electr M 2017;6:19–23.
[30] Ko T, Lee J, Ryu D. Blockchain technology and manufacturing industry: real-time transparency and cost savings. Sustainability-Basel 2018;10:4274.
[31] Min H. Blockchain technology for enhancing supply chain resilience. Bus Horiz 2019;62:35–45.
[32] Leng J, Zhang H, Yan D, Liu Q, Chen X, Zhang D. Digital twin-driven manufacturing cyber-physical system for parallel controlling of smart workshop. J Amb Intel Hum Comp 2019;10:1155–66.
[33] Kennedy ZC, Stephenson DE, Christ JF, Pope TR, Arey BW, Barrett CA, et al. Enhanced anti-counterfeiting measures for additive manufacturing: coupling lanthanide nanomaterial chemical signatures with blockchain technology. J Mater Chem C 2017;5:9570–8.
[34] Ren L, Zheng S, Zhang L. A blockchain model for industrial internet. IEEE; 2018. p. 791–4.
[35] Schmidt R, Möhring M, Keller B, Zimmermann A. Potentials of smart contracts-based disintermediation in additive manufacturing supply chains. Twenty-fifth americas conference on information systems. Mexico: Cancun; 15-17 Aug. 2019. p. 1–5.
[36] Tijan E, Aksentijević S, Ivanić K, Jardas M. Blockchain technology implementation in logistics. Sustainability-Basel 2019;11:1185.
[37] Heinrichs H. Sharing economy: a potential new pathway to sustainability. Gaia 2013;22:228.
[38] Venkatesh VG, Kang K, Wang B, Zhong RY, Zhang A. System architecture for blockchain based transparency of supply chain social sustainability. Robot Cim-Int Manuf. 2020;63:101896.
[39] Prahalad CK, Ramaswamy V. Co-creation experiences: the next practice in value creation. J Interact Market 2004;18:5–14.
[40] Leng J, Jiang P, Liu C, Wang C. Contextual self-organizing of mass individualization process under social manufacturing paradigm: a cyber-physical-social system approach. Enterp Inf Syst-Uk 2018:10–1080. Online.
[41] Chung K, Yoo H, Choe D, Jung H. Blockchain network based topic mining process for cognitive manufacturing. Wireless Pers Commun 2019;105:583–97.
[42] Barenji AV, Li Z, Wang WM, Huang GQ, Guerra-Zubiaga DA. Blockchain-based ubiquitous manufacturing: a secure and reliable cyber-physical system. Int J Prod Res 2020;58:2200–21.
[43] Nikolakis W, John L, Krishnan H. How blockchain can shape sustainable global value chains: an evidence, verifiability, and enforceability (EVE) framework. Sustainability-Basel 2018;10:3926.
[44] Geiger S, Schall D, Meixner S, Egger A. Process traceability in distributed manufacturing using blockchains. In: Proceedings of the 34th ACM/SIGAPP symposium on applied computing. Limassol, Cyprus; 2019. p. 417–20. April 08 - 12.
[45] Zareiyan B, Korjani M. Blockchain technology for global decentralized manufacturing: challenges and solutions for supply chain in fourth industrial revolution. Int J Adv Robot Autom 2018;3:1–10.
[46] Li Z, Guo H, Barenji AV, Wang WM, Guan Y, Huang GQ. A sustainable production capability evaluation mechanism based on blockchain, LSTM, analytic hierarchy process for supply chain network. Int J Prod Res 2020:1–21. https://doi.org/10.1080/00207543.2020.1740342.
[47] Wang F. From social computing to social manufacturing: the coming industrial revolution and new frontier in cyber-physical-social space. Bull Chin Acad Sci 2012;6:658–69.
[48] Tapscott D, Tapscott A. How blockchain will change organizations. Mit Sloan Manage Rev 2017;58:10–3.
[49] Pazaitis A, De Filippi P, Kostakis V. Blockchain and value systems in the sharing economy: the illustrative case of Backfeed. Technol Forecast Soc Change 2017; 125:105–15.
[50] Leng J, Liu J, Jiang P. Blockchain models for cyber-credits of social manufacturing. In: Social manufacturing: fundamental and application. Springer International Publishing; 2018. https://doi.org/10.1007/978-3-319-72986-2_9.
[51] Liu J, Jiang P, Leng J. A framework of credit assurance mechanism for manufacturing services under social manufacturing context. In: 13th IEEE conference on automation science and engineering (CASE). Xi'an. China: IEEE; 2017. p. 36–40.
[52] Angrish A, Craver B, Hasan M, Starly B. A case study for Blockchain in manufacturing:"FabRec": a prototype for peer-to-peer network of manufacturing nodes. Procedia Manuf 2018;26:1180–92.
[53] Li L, Zheng Y, Yang M, Leng J, Cheng Z, Xie Y, et al. A survey of feature modeling methods: historical evolution and new development. Robot Cim-Int Manuf. 2020; 61:101851.
[54] Li Z, Wang WM, Liu G, Liu L, He J, Huang GQ. Toward open manufacturing: a cross-enterprises knowledge and services exchange framework based on blockchain and edge computing. Ind Manag Data Syst 2018;118:303–20.
[55] Gong X. Collaborative-crowdsourcing product fulfillment for open design and manufacturing. 2018. http://hdl.handle.net/1853/59956.
[56] Li Z, Liu L, Barenji AV, Wang W. Cloud-based manufacturing blockchain: secure knowledge sharing for injection mould redesign. Procedia CIRP 2018;72:961–6.
[57] Barenji AV, Li Z, Wang WM. Blockchain cloud manufacturing: shop floor and machine level. In: European conference on smart objects, systems and technologies; 12-13 June 2018. p. 1–6. Munich, Germany.
[58] Bahga A, Madisetti VK. Blockchain platform for industrial internet of things. J Software Eng Appl 2016;9:533–46.
[59] Li Z, Barenji AV, Huang GQ. Toward a blockchain cloud manufacturing system as a peer to peer distributed network platform. Robot Cim-Int Manuf. 2018;54: 133–44.
[60] Innerbichler J, Damjanovic-Behrendt V. Federated byzantine agreement to ensure trustworthiness of digital manufacturing platforms. In: Proceedings of the 1st workshop on cryptocurrencies and blockchains for distributed systems. Munich, Germany: ACM; 2018. p. 111–6. June 15 - 15, 2018.
[61] Yu C, Zhang L, Zhao W, Zhang S. A blockchain-based service composition architecture in cloud manufacturing. Int J Comput Integrated Manuf 2019:1–11.
[62] Leevinson JR, Vijayaraghavan V, Dammodaran M. Blockchain mechanisms as security-enabler for industrial IoT applications. In: The internet of things in the industrial sector. Springer; 2019. p. 145–62.
[63] Zhao S, Li S, Yao Y. Blockchain enabled industrial internet of things technology. IEEE T Comput Soc Syst 2019:1–12.

[64] Huang J, Kong L, Chen G, Wu M, Liu X, Zeng P. Towards secure industrial IoT: blockchain system with credit-based consensus mechanism. IEEE T Ind Inform 2019;15:3680–9.
[65] Wan J, Li J, Imran M, Li D. A blockchain-based solution for enhancing security and privacy in smart factory. IEEE T Ind Inform 2019;15:3652–60.
[66] Ma M, Shi G, Li F. Privacy-oriented blockchain-based distributed key management architecture for hierarchical access control in the IoT scenario. IEEE Access 2019;7:34045–59.
[67] Qiu C, Yu FR, Yao H, Jiang C, Xu F, Zhao C. Blockchain-based software-defined industrial internet of things: a dueling deep -learning approach. IEEE Internet Things 2019;6:4627–39.
[68] Miller D. Blockchain and the internet of things in the industrial sector. IT Prof 2018;20:15–8.
[69] Liu Q, Leng J, Yan D, Zhang D, Wei L, Yu A, et al. Digital twin-based designing of the configuration, motion, control, and optimization model of a flow-type smart manufacturing system. J Manuf Syst 2020. https://doi.org/10.1016/j.jmsy.2020.04.012.
[70] Teslya N. Industrial socio-cyberphysical system's consumables tokenization for smart contracts in blockchain. In: International conference on business information systems. Seville, Spain; 26-28 June 2019. p. 344–55.
[71] Stanciu A. Blockchain based distributed control system for edge computing. In: 21st international conference on control systems and computer science (CSCS); 29-31 May 2017. p. 667–71. Bucharest, Romania.
[72] Meyer T, Kuhn M, Hartmann E. Blockchain technology enabling the Physical Internet: a synergetic application framework. Comput Ind Eng 2019;136:5–17.
[73] Raschendorfer A, Mörzinger B, Steinberger E, Pelzmann P, Oswald R, Stadler M, et al. On IOTA as a potential enabler for an M2M economy in manufacturing. Procedia CIRP 2019;79:379–84.
[74] Bose S, Raikwar M, Mukhopadhyay D, Chattopadhyay A, Lam K. BLIC: a blockchain protocol for manufacturing and supply chain management of ICS. IEEE; 2018. p. 1326–35.
[75] Adhikari A, Winslett M. A hybrid architecture for secure management of manufacturing data in industry 4.0. In: International conference on pervasive computing and communications; 2019. p. 973–8.
[76] Sikorski JJ, Haughton J, Kraft M. Blockchain technology in the chemical industry: machine-to-machine electricity market. Appl Energy 2017;195:234–46.
[77] Pinheiro P, Macedo M, Barbosa R, Santos R, Novais P. Multi-agent systems approach to industry 4.0: enabling collaboration considering a blockchain for knowledge representation. In: International conference on practical applications of agents and multi-agent systems; 2018. p. 149–60. Toledo, Spain. June 20–22.
[78] Guo J, Lu Z. A supply chain information system of the supply-hub based on blockchain. In: Zhao H, editor. Advances in social science education and humanities research; 2018. p. 88–91.
[79] Swan M. Chapter five - blockchain for business: next-generation enterprise artificial intelligence systems. Adv Comput 2018;111:121–62.
[80] Lin J, Shen Z, Miao C, Liu S. Using blockchain to build trusted LoRaWAN sharing server. Int J Crowd Sci 2017;1:270–80.
[81] Hammi B, Hammi MT, Bellot P, Serhrouchni A. Bubbles of Trust: a decentralized blockchain-based authentication system for IoT. Comput Secur 2018;78:126–42.
[82] Lin C, He D, Huang X, Choo KR, Vasilakos AV. BSeIn: a blockchain-based secure mutual authentication with fine-grained access control system for industry 4.0. J Netw Comput Appl 2018;116:42–52.
[83] Ren Y, Zhu F, Qi J, Wang J, Sangaiah AK. Identity management and access control based on blockchain under edge computing for the industrial internet of things. Appl Sci-Basel 2019;9:2058.
[84] Chen H, Irawan B, Shae Z. A cooperative evaluation approach based on blockchain technology for IoT application. In: International conference on innovative mobile and internet services in ubiquitous computing; 2018. p. 913–21.
[85] Fernandez-Carames TM, Blanco-Novoa O, Froiz-Miguez I, Fraga-Lamas P. Towards an autonomous industry 4.0 warehouse: a UAV and blockchain-based system for inventory and traceability applications in big data-driven supply chain management. Sensors-Basel. 2019;19(10):2394.
[86] Kapitonov A, Lonshakov S, Krupenkin A, Berman I. Blockchain-based protocol of autonomous business activity for multi-agent systems consisting of UAVs. IEEE; 2017. p. 84–9.
[87] Jiang P, Cao W. An RFID-driven graphical formalized deduction for describing the time-sensitive state and position changes of work-in-progress material flows in a job-shop floor. J Manuf Sci E-T Asme. 2013;135.
[88] Leng J, Jiang P. A deep learning approach for relationship extraction from interaction context in social manufacturing paradigm. Knowl-Based Syst. 2016;100:188–99.
[89] ArnabBanerjee. Chapter three - blockchain technology: supply chain insights from ERP. Adv Comput 2018;111:69–98.
[90] Pethuru R, Chandra DG. Blockchain technology: supply chain insights from ERP. Adv Comput 2018;111:69–98.
[91] Wang Y, Kogan A. Designing confidentiality-preserving Blockchain-based transaction processing systems. Int J Account Inf Syst 2018;30:1–18.
[92] Leng J, Jiang P. Evaluation across and within collaborative manufacturing networks: a comparison of manufacturers' interactions and attributes. Int J Prod Res 2018;56:5131–46.
[93] Xia J, Yongjun L. Trust evaluation model for supply chain enterprises under blockchain environment. In: Proceedings of the 2017 7th international conference on social network, communication and education. Atlantis Press; 2017. Shenyang, China, on July 28-30, 2017.
[94] Dolgui A, Ivanov D, Potryasaev S, Sokolov B, Ivanova M, Werner F. Blockchain-oriented dynamic modelling of smart contract design and execution in the supply chain. Int J Prod Res 2020;58(7):2184–99.
[95] Zhang Y, Zhang P, Tao F, Liu Y, Zuo Y. Consensus aware manufacturing service collaboration optimization under blockchain based Industrial Internet platform. Comput Ind Eng 2019;135:1025–35.
[96] Liu Q, Zhang H, Leng J, Chen X. Digital twin-driven rapid individualised designing of automated flow-shop manufacturing system. Int J Prod Res 2019;57:3903–19.
[97] Zhang H, Liu Q, Chen X, Zhang D, Leng J. A digital twin-based approach for designing and multi-objective optimization of hollow glass production line. IEEE Access 2017;5:26901–11.
[98] Lemeš S, Lemeš L. Blockchain in distributed CAD environments. In: International conference "new technologies, development and applications". Sarajevo, Bosnia and Herzegovina; 27-29 June 2019. p. 25–32.
[99] Comuzzi M, Unurjargal E, Lim C. Towards a design space for blockchain-based system reengineering. In: International conference on advanced information systems engineering; 3-7 June 2019. p. 138–43. Rome, Italy.
[100] Liu XL, Wang WM, Guo H, Barenji AV, Li Z, Huang GQ. Industrial blockchain based framework for product lifecycle management in industry 4.0. Robot Cim-Int Manuf. 2020;63:101897.
[101] Huang J, Li S, Thürer M. On the use of blockchain in industrial product service systems: a critical review and analysis. Procedia CIRP 2019;83:552–6.
[102] Kamble S, Gunasekaran A, Arha H. Understanding the Blockchain technology adoption in supply chains-Indian context. Int J Prod Res 2019;57:2009–33.
[103] Fu B, Shu Z, Liu X. Blockchain enhanced emission trading framework in fashion apparel manufacturing industry. Sustainability-Basel 2018;10:1105.
[104] Patel P, Ali MI, Sheth A. From raw data to smart manufacturing: AI and semantic web of things for industry 4.0. IEEE Intell Syst 2018;33:79–86.
[105] Madhwal Y, Panfilov PB. Industrial case: blockchain on aircraft's parts supply chain management. In: American Conference on Information Systems 2017 Workshop on Smart Manufacturing Proceedings, 6; 2017. p. 1–6.
[106] Leng J, Chen Q, Mao N, Jiang P. Combining granular computing technique with deep learning for service planning under social manufacturing contexts. Knowl-Based Syst. 2018;143:295–306.
[107] Baumung W, Fomin V. Framework for enabling order management process in a decentralized production network based on the blockchain-technology. Procedia CIRP 2019;79:456–60.
[108] Bulbul S, Ince G. Blockchain-based framework for customer loyalty program. IEEE; 2018. p. 342–6.
[109] Yoo M, Won Y. A study on the transparent price tracing system in supply chain management based on blockchain. Sustainability-Basel. 2018;10:4037.
[110] Narayanaswami C, Nooyi R, Govindaswamy SR, Viswanathan R. Blockchain anchored supply chain automation. IBM J Res Dev 2019;63:1–11.
[111] Lee Y, Lee KM, Lee SH. Blockchain-based reputation management for custom manufacturing service in the peer-to-peer networking environment. Peer Peer Netw Appl 2019:1–13.
[112] Frey R, Wörner D, Ilic A. Collaborative filtering on the blockchain: a secure recommender system for e-commerce. In: Twenty-second americas conference on information systems; 2016. p. 1–5. San Diego, CA, USA. Aug. 11-13, 2016.
[113] Papakostas N, Newell A, Hargaden V. A novel paradigm for managing the product development process utilising blockchain technology principles. CIRP Ann - Manuf Technol 2019;68:137–40.
[114] Pinheiro P, Santos R, Barbosa R. Industry 4.0 multi-agent system based knowledge representation through blockchain. In: International symposium on ambient intelligence. Ávila, Spain; 26-28 June 2019. p. 331–7.
[115] Adhikari A, Winslett M. A hybrid architecture for secure management of manufacturing data in industry 4.0. In: IEEE international conference on pervasive computing and communications workshops. Kyoto, Japan; 11-15 March 2019. p. 973–8.
[116] Li Z, Liu X, Wang WM, Vatankhah Barenji A, Huang GQ. CKshare: secured cloud-based knowledge-sharing blockchain for injection mold redesign. Enterp Inf Syst-Uk 2019;13:1–33.
[117] Zhang H, Li S, Yan W, Jiang Z, Wei W. A knowledge sharing framework for green supply chain management based on blockchain and edge computing. In: International conference on sustainable design and manufacturing; July 04-05 2019. p. 413–20. Budapest, Hungary.
[118] Kouhizadeh M, Sarkis J, Zhu Q. At the nexus of blockchain technology, the circular economy, and product deletion. Appl Sci-Basel 2019;9:1712.
[119] Zhu Q, Kouhizadeh M. Blockchain technology, supply chain information, and strategic product deletion management. IEEE Eng Manag Rev 2019;47:36–44.
[120] Ying W, Pee LG, Jia S. Social informatics of intelligent manufacturing ecosystems: a case study of KuteSmart. Int J Inf Manag 2018;42:102–5.
[121] Engelmann F, Holland M, Nigischer C, Stjepandic J. Intellectual property protection and licensing of 3D print with blockchain technology. In: Peruzzini M, Pellicciari M, Bil C, Stjepandic J, Wognum N, editors. Advances in transdisciplinary engineering; 2018. p. 103–12.
[122] Marques M, Agostinho C, Zacharewicz G, Jardim-Goncalves R. Decentralized decision support for intelligent manufacturing in Industry 4.0. J Amb Intel Smart En 2017;9:299–313.
[123] Di Ciccio C, Cecconi A, Mendling J, Felix D, Haas D, Lilek D, et al. Blockchain-based traceability of inter-organisational business processes. In: Shishkov B, editor. Lecture notes in business information processing; 2018. p. 56–68.
[124] Viriyasitavat W, Xu LD, Bi Z, Sapsomboon A. Blockchain-based business process management (BPM) framework for service composition in industry 4.0. J Intell Manuf 2018:10–1007.

[125] Wang G, Shi ZJ, Nixon M, Han S. SMChain: a scalable blockchain protocol for secure metering systems in distributed industrial plants. In: Ramachandran GS, Ortiz J, editors; 2019. p. 249–54.
[126] Sharma PK, Kumar N, Park JH. Blockchain-based distributed framework for automotive industry in a smart city. IEEE T Ind Inform 2019;15:4197–205.
[127] Rožman N, Vrabič R, Corn M, Požrl T, Diaci J. Distributed logistics platform based on Blockchain and IoT. Procedia CIRP 2019;81:826–31.
[128] Zhang Y, Wen J. The IoT electric business model: using blockchain technology for the internet of things. Peer Peer Netw Appl 2017;10:983–94.
[129] Nowiński W, Kozma M. How can blockchain technology disrupt existing business models? Entrepreneurial Bus Econ Rev 2017;5:173–88.
[130] Chen S, Shi R, Ren Z, Yan J, Shi Y, Zhang J. A blockchain-based supply chain quality management framework. IEEE; 2017. p. 172–6.
[131] ElMessiry M, ElMessiry A. Blockchain framework for textile supply chain management. In: International conference on blockchain; June 25-30, 2018. p. 213–27. Seattle, WA, USA.
[132] Marfia G, Esposti PD. Blockchain and sensor-based reputation enforcement for the support of the reshoring of business activities. In: Vecchi A, editor. Reshoring of manufacturing. Springer; 2017. p. 125–39.
[133] Alzahrani N, Bulusu N. Block-supply chain: a new anti-counterfeiting supply chain using NFC and blockchain. Proceedings of the 1st workshop on cryptocurrencies and blockchains for distributed systems. Munich, Germany. June 15 - 15, 2018. p. 30-35.
[134] Lu D, Moreno-Sanchez P, Zeryihun A, Bajpayi S, Yin S, Feldman K, et al. Reducing automotive counterfeiting using blockchain: benefits and challenges. IEEE; 2019. p. 39–48.
[135] Haq I, Muselemu O. Blockchain technology in pharmaceutical industry to prevent counterfeit drugs. Int J Comput Appl 2018;180:8–12.
[136] Tseng J, Liao Y, Chong B, Liao S. Governance on the drug supply chain via Gcoin blockchain. Int J Environ Res Publ Health 2018;15:1055.
[137] Wu X, Lin Y. Blockchain recall management in pharmaceutical industry. Procedia CIRP 2019;83:590–5.
[138] Steinwandter V, Herwig C. Provable data integrity in the pharmaceutical industry based on version control systems and the blockchain. PDA J Pharm Sci Technol 2019;73:373–90.
[139] Sylim P, Liu F, Marcelo A, Fontelo P. Blockchain technology for detecting falsified and substandard drugs in distribution: pharmaceutical supply chain intervention. JMIR Res Protoc 2018;7:e10163.
[140] Vruddhula S. Application of on-dose identification and blockchain to prevent drug counterfeiting. Pathog Glob Health 2018;112:161.
[141] Holland M, Nigischer C, Stjepandic J. Copyright protection in additive manufacturing with blockchain approach. In: Chen CH, Trappey AC, Peruzzini M, Stjepandic J, Wognum N, editors. Advances in transdisciplinary engineering; 2017. p. 914–21.
[142] Mandolla C, Petruzzelli AM, Percoco G, Urbinati A. Building a digital twin for additive manufacturing through the exploitation of blockchain: a case analysis of the aircraft industry. Comput Ind 2019;109:134–52.
[143] Yampolskiy M, King WE, Gatlin J, Belikovetsky S, Brown A, Skjellum A, et al. Security of additive manufacturing: attack taxonomy and survey. Additive Manufacturing 2018;21:431–57.
[144] Hepp T, Wortner P, Schönhals A, Gipp B. Securing physical assets on the blockchain: linking a novel object identification concept with distributed ledgers. In: Proceedings of the 1st workshop on cryptocurrencies and blockchains for distributed systems; June 15 - 15, 2018. p. 60–5. Munich, Germany.
[145] Wang S, Wang J, Guo J, Du Y, Cheng S, Li X. A summary of research on blockchain in the field of intellectual property. Procedia Comput Sci 2019;147: 191–7.
[146] Westerkamp M, Victor F, Küpper A. Blockchain-based supply chain traceability: token recipes model manufacturing processes. In: IEEE international conference on internet of thing and IEEE green computing and communications and IEEE cyber, physical and social computing and IEEE smart data; 30 July-3 Aug. 2018. Halifax, NS, Canada.
[147] Kim HM, Laskowski M. Toward an ontology-driven blockchain design for supply-chain provenance. Intell Syst Account Finance Manag 2018;25:18–27.
[148] Mondragon AEC, Mondragon CEC, Coronado ES. Exploring the applicability of blockchain technology to enhance manufacturing supply chains in the composite materials industry. IEEE 2018:1300–3.
[149] Islam MN, Patii VC, Kundu S. On IC traceability via blockchain. In: International symposium on VLSI design, automation and test. Hsinchu, taiwan; 16-19 April 2018. p. 1–4.
[150] Mondragon AEC, Coronado CE, Coronado ES. Investigating the applicability of distributed ledger/blockchain technology in manufacturing and perishable goods supply chains. IEEE; 2019. p. 728–32.
[151] Francisco K, Swanson D. The supply chain has No clothes: technology adoption of blockchain for supply chain transparency. Logistics 2018;2:2.
[152] Agrawal TK, Sharma A, Kumar V. Blockchain-based secured traceability system for textile and clothing supply chain. In: Artificial intelligence for fashion industry in the big data era. Springer; 2018. p. 197–208.
[153] Westerkamp M, Victor F, Küpper A. Tracing manufacturing processes using blockchain-based token compositions. Digit Commun Netw 2020;6(2):167–76.
[154] Xu X, Lu Q, Liu Y, Zhu L, Yao H, Vasilakos AV, et al. Designing blockchain-based applications a case study for imported product traceability. Future Generat Comput Syst 2019;92:399–406.
[155] Kouhizadeh M, Sarkis J. Blockchain practices, potentials, and perspectives in greening supply chains. Sustainability-Basel. 2018;10:3652.
[156] Xu X, Rahman F, Shakya B, Vassilev A, Forte D, Tehranipoo M. Electronics supply chain integrity enabled by blockchain. ACM Trans Des Autom Electron Syst 2019; 24.
[157] Tozanlı Ö, Kongar E, Gupta SM. Trade-in-to-upgrade as a marketing strategy in disassembly-to-order systems at the edge of blockchain technology. Int J Prod Res 2020:1–18.
[158] Saberi S, Kouhizadeh M, Sarkis J, Shen L. Blockchain technology and its relationships to sustainable supply chain management. Int J Prod Res 2019;57: 2117–35.
[159] Jain VN, Mishra D. Blockchain for supply chain and manufacturing industries and future it holds! Int J Eng Techn Res 2018;7:32–9.
[160] Lacity MC. Addressing key challenges to making enterprise blockchain applications a reality. MIS Q Exec 2018;17:201–22.
[161] Yadav S, Singh SP. An integrated fuzzy-ANP and fuzzy-ISM approach using blockchain for sustainable supply chain. J Enterprise Inf Manag 2020:1–25.
[162] Huckle S, White M. Socialism and the blockchain. Future Internet 2016;8:49.
[163] Tiscini R, Testarmata S, Ciaburri M, Ferrari E. The blockchain as a sustainable business model innovation. Manag Decis 2020. https://doi.org/10.1108/MD-09-2019-1281.
[164] Fiaidhi J, Mohammed S, Mohammed S. EDI with blockchain as an enabler for extreme automation. It Prof 2018;20:66–72.
[165] Zhang A, Zhong RY, Farooque M, Kang K, Venkateshe VG. Blockchain-based life cycle assessment: an implementation framework and system architecture. Resour Conserv Recycl 2020;152:104512.
[166] Yadav S, Singh SP. Blockchain critical success factors for sustainable supply chain. Resour Conserv Recycl 2020;152:104505.
[167] Venkatesh VG, Kang K, Wang B, Zhong RY, Zhang A. System architecture for blockchain based transparency of supply chainsocial sustainability. Robot Cim-Int Manuf. 2020;63:101896.
[168] Queiroz MM, Fosso Wamba S. Blockchain adoption challenges in supply chain: an empirical investigation of the main drivers in India and the USA. Int J Inf Manag 2019;46:70–82.
[169] Bai L, Hu M, Liu M, Wang J. BPIIoT: a light-weighted blockchain-based platform for industrial IoT. IEEE Access 2019;7:58381–93.
[170] Kiktenko EO, Pozhar NO, Anufriev MN, Trushechkin AS, Yunusov RR, Kurochkin YV, et al. Quantum-secured blockchain. Quan Sci Technol 2018;3: 35004.
[171] Jiang Y, Chen CLP, Duan J. A new practice-driven approach to develop software in a cyber-physical system environment. Enterp Inf Syst-Uk 2016;10:211–27.
[172] Cai W, Wang Z, Ernst JB, Hong Z, Feng C, Leung VCM. Decentralized applications: the blockchain-empowered software system. IEEE Access 2018;6:53019–33.
[173] Peck ME. Blockchain world - do you need a blockchain? This chart will tell you if the technology can solve your problem. IEEE Spectrum 2017;54:38–60.
[174] Fernandez-Carames TM, Fraga-Lamas P. A review on the application of blockchain to the next generation of cybersecure industry 4.0 smart factories. IEEE Access 2019;7:45201–18.
[175] Narayan R, Tidström A. Tokenizing coopetition in a blockchain for a transition to circular economy. J Clean Prod 2020;263:121437.
[176] Babich V, Hilary G. Distributed ledgers and operations: what operations management researchers should know about blockchain technology. M&SOM-Manuf Serv Oper Manag. 2019:10–1287.
[177] Allen DWE, Berg C, Davidson S, Novak M, Potts J. International policy coordination for blockchain supply chains. Asia & the Pacific Policy Studies 2019. https://doi.org/10.1002/app5.281.
[178] Lima C. Developing open and interoperable DLT\/Blockchain standards [standards]. Computer 2018;51:106–11.
[179] Anjum A, Sporny M, Sill A. Blockchain standards for compliance and trust. IEEE Cloud Comput 2017;4:84–90.
[180] Backman J, Yrjola S, Valtanen K, Mammela O. Blockchain network slice broker in 5G: slice leasing in factory of the future use case. IEEE 2017:1–8.
[181] Li Z, Guo H, Wang WM, Guan Y, Barenji AV, Huang GQ, et al. A blockchain and AutoML approach for open and automated customer service. IEEE T Ind Inform 2019;15:3642–51.
[182] Leng J, Jiang P. Mining and matching relationships from interaction contexts in a social manufacturing paradigm. IEEE T Syst Man Cybern -Syst. 2017;47:1–13.
[183] Rabah K. Convergence of AI, IoT, big data and blockchain: a review. Lake Ins J 2018;1:1–18.