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Scalability Solutions in Blockchain-Supported Manufacturing: A Survey

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Researchers in the field of smart manufacturing have recognized the benefits of blockchain technology, which solves the trust problem in the open network without relying on any trusted third party. Blockchain technology enables interaction between otherwise competing manufacturing entities to satisfy increasing customer demands in a trustful way. However, existing blockchain networks are facing limitations, which are defined by the trade-off between scalability, decentralization, and security. The scalability of the blockchain network is defined as the ability of the network to support an increasing load of transactions and it is lower compared to the non-blockchain systems. In order to omit the effects of the limitations, scalability solutions are being presented. This research reviews the literature in the field of blockchain-supported manufacturing concerning scalability solutions. The selected literature has been reviewed and classified according to the type of scalability solution. For each type of scalability solution, the main features of the concepts and connection between blockchain technology and manufacturing system are highlighted and discussed. The main findings of the study are that Layer 1 scalability solutions are better represented in the literature and are predominating in the case of general smart manufacturing systems, whereas Layer 2 scalability solutions are better represented in the case of specific smart manufacturing systems. Based on insights obtained from the presented analysis, future directions and open issues regarding the scalability limitations and solutions in blockchain-supported manufacturing are presented.

Keywords: blockchain, manufacturing, scalability, trilemma

Highlights

- *The literature on scalability solutions in blockchain-supported manufacturing does not follow the trends of publications in the field of scalability solutions.*
- *Most solutions employ the consensus mechanism, off-chain solutions, or optimize blockchain structures.*
- *Layer 1 scalability solutions are better represented than Layer 2 solutions. Layer 1 solutions are predominating in the case of general smart manufacturing systems and Layer 2 in specific smart manufacturing systems.*
- *The research on scalability limitations in blockchain-supported manufacturing is increasing and improving over time.*
- *Major open issue with the literature proposed solutions is a lack of implementation in the industry and insufficient analysis of the scalability trilemma in connection with practical limitations.*

0 INTRODUCTION

In recent years, we have witnessed an increase in the literature introducing blockchain technology in the field of manufacturing [1]. Technological advances and the stringent requirements of Industry 4.0 have resulted in new concepts of smart manufacturing systems. Manufacturing systems are formed into complex organizational networks that take advantage of a high level of digitized manufacturing segments to meet as many diverse customers' needs as possible [2]. Individual manufacturing activities are packaged in services that are available on shared virtual platforms (service-oriented architecture) [3]. By connecting through such organized networks, manufacturers can meet a larger number and more diverse market requirements. As there are interactions between production entities that have different owners, the problem of trust in the operation of the system arises. Typically, centrally managed platforms that allowed the integration of production entities were identified as weaknesses in the system, mainly from a security perspective [4].

Blockchain technology, which was implemented in response to the manipulations of centralized organizations in the banking system, is presented as an answer to the problem of ensuring trust between competing entities participating in global networks [4]. In conjunction with smart manufacturing networks, it can ensure that interactions between individual entities in the system are recorded, in a self-executing manner, in a transparent and immutable blockchain maintained by a decentralized network [5]. So far, these features have been used in manufacturing to address various cyber security issues in smart manufacturing systems (SMS) to increase trust in the system [6].

However, blockchain technology also has certain limitations. The limitations of blockchain technology are represented by the scalability trilemma [7]. Similar to the consistency, availability, and partition tolerance (CAP) theorem [8] in the traditional field of the distributed system, a trade-off occurs between three blockchain network properties, namely:

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scalability, security, and decentralization. In the currently existing major public blockchain networks (e.g. Bitcoin, Ethereum), it has repeatedly happened that the network failed to process a large increase of transaction requests resulting in much longer waiting times than usual for transactions to be processed. Scalability limitations of blockchain technology thus affected the operation of the blockchain-supported systems [9]. Due to the limited transaction throughput, pending transactions are waiting longer in line to be confirmed. Priority in line is defined by a set transaction fee, therefore, the transaction fee increases due to the competition for faster confirmation. The reduced number of nodes storing the whole ever-growing blockchain results in delays when querying data from the blockchain.

Global manufacturing networks are big and a large number of interactions between entities can be assumed. This, in turn, means that the traditional approach of implementing blockchain technology in manufacturing systems would not satisfy the performance requirements and at the same time ensure decentralization and security (which creates the trust). For example, if the frequency of incoming transactions from the manufacturing system exceeds the frequency of transaction confirmation of the blockchain network (e.g. Ethereum confirms 15 transactions per second), the manufacturing system would be affected by the scalability limitations of the blockchain technology. However, scalability solutions have already been presented in the field of blockchain technology, which can increase scalability or enable the change of blockchain network properties according to the trilemma and thus offer different properties according to user requirements.

There are already several published literature reviews on the topic of integrating blockchain technology into manufacturing. A survey was made regarding different aspects of the engineering and manufacturing processes where researchers or developers have already proposed or applied blockchain [1]. Similar research was conducted regarding the existing blockchain applications in Industry 4.0 and industrial internet of things (IIoT) settings [10]. Another survey discusses the research progress of blockchain-secured smart manufacturing and how blockchain technology is applied to address cybersecurity issues in the smart manufacturing system [6]. The research was also presented regarding the literature on achieving sustainability by employing blockchain technology in manufacturing systems and product lifecycle management [11].

However, so far no one has discussed how the presented concepts of blockchain-supported manufacturing take into account the constraint on scalability that blockchain technology introduces into manufacturing. In this paper, a review of the literature on the scalability solutions applied in blockchain-supported manufacturing is presented. The main contributions of the paper are summarized as follows:

- Literature addressing the problem of scalability and scalability solutions in blockchain-supported manufacturing is identified and classified according to existing scalability solutions. The main features of emerging concepts are presented.
- The literature is analyzed regarding the type of scalability solutions, the type of manufacturing system, and the extent of concept presentation.
- Based on the analysis, future directions and open issues in research regarding the scalability limitations in blockchain-supported manufacturing are given.

1 BLOCKCHAIN TECHNOLOGY IN MANUFACTURING

1.1 Blockchain Technology

A blockchain is a distributed database where an ordered list of various records is stored on. Records are stored in blocks connected through links in form of a chain [12]. The links between blocks are made with the use of asymmetric cryptography [13]. Each record in the blockchain made by a user is signed with a set of encryption keys that are self-managed and unique [14]. Nodes in the blockchain network are communicating with each other to establish synchronization of the written data in the blockchain.

The key properties of the blockchain network are:

- decentralized consensus,
- immutability of the records,
- transparent database,
- self-executing environment.

The first key property of the blockchain network is its ability to reach a consensus among the nodes in the network (solving Byzantine generals problems [15]). Consensus must be reached for every change of data written on the blockchain (e.g. new transaction). The consensus mechanism represents democratic voting on the changes of the written records on the blockchain and it further means that all of the written changes of the blockchain were made in agreement of the majority of the participants in the transaction confirmation on the blockchain network. This coordination between nodes in the network instills trust that the data in the blockchain was written correctly and without tempering, [16]. There exist two types of blockchain networks that are distinguished according to how openness to participation in the consensus mechanism is defined, namely: permissioned and permissionless [17]. Permissioned networks allow only selected confirmators to join the consensus mechanism and permissionless allow anyone to join the consensus process in the network.

Because of the decentralized consensus, tampering with existing data written on the blockchain is almost impossible. It is only possible if the majority of the nodes in the network agree to the changes. Therefore, blockchain technology offers immutability of the records [18]. Again, there exist two types of blockchain networks regarding access to the usage of the blockchain network and the access to the data written on the blockchain, namely: private and public [19]. Private blockchain networks have a strictly defined list of users that can create new transactions and have access to the written transactions on the blockchain. Public blockchain networks on the other side enable anyone to create transactions and the whole blockchain is publicly accessible. In both types of blockchain networks, users that have access to the blockchain can verify which blockchain data was written and when it was written on the blockchain, meaning that blockchain technology provides a transparent database.

The last key property of blockchain technology is that it enables a self-executing environment. By providing a virtual environment on the blockchain network, developers can code an assortment of automated procedures into digital transactions [20]. These programs are named smart contracts and are digital contracts allowing terms contingent on the decentralized consensus that is tamper-proof and typically self-enforcing through automated execution [21]. By employing smart contracts, different procedures directly related to the change of written data on the blockchain can be executed automatically.

Observing diverse blockchain networks leads to the conclusion that blockchain networks are unable to scale effectively [22], the networks are susceptible to various security vulnerabilities [18], and are prone to centralization [23]. These observations and research conclusions about the current state of blockchain networks were being joined into a single idea named the scalability trilemma (Fig. 1) [24] and [25]. One definition of the Trilemma states that when someone is trying to optimize a blockchain-supported system, there exists a trade-off between three important properties: scalability, decentralization, and security [7].

Table 1. *Definition of blockchain network properties terms*

Term	Definition
Scalability	The ability of the blockchain network to support an increasing load of transactions [26].
Decentralization	The number of nodes in the blockchain network participating in the process of transaction confirmation [27].
Security	The ability of the blockchain network to defend itself against attackers with a certain amount of resources [28].

For example, adding a centralized coordinator into the system to increase the speed of the consensus process would result in a more centralized system. Another example, shortening the block interval can increase the transaction throughput but also affects the security of the whole system because nodes are not synchronized. Therefore, balancing or even achieving these three aspects of the blockchain system well is essential for the future development of blockchain that is suitable for more complex and larger-scale scenes in our daily lives [29].

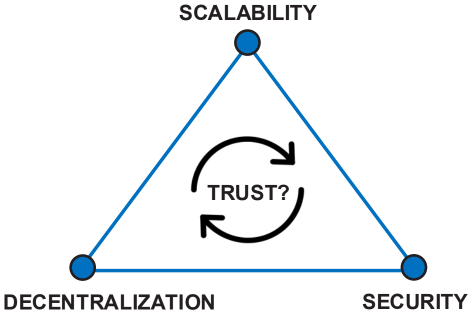


Fig. 1. *The scalability trilemma*

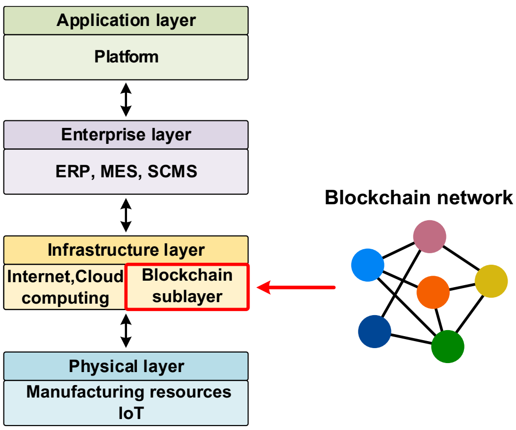
Where an individual blockchain network is positioned according to its characteristics affects users' trust in the operation of that network [30]. Trust is a psychological state comprising the intention to accept vulnerability based upon positive expectations of the intentions or behavior of another [31]. Trust in the correct execution of the consensus mechanism and recorded data on the blockchain increases with decentralization and security. Mainly because a stronger consensus has been established among a larger number of entities involved in the validation of new blocks. This, in turn, means that if we move towards a more scalable system with the properties of blockchain technology, trust in the system reduces. However, it is difficult to define how exactly is trust dependent on the three properties of the blockchain network (Fig. 1).

1.2 Blockchain-Supported Manufacturing

The four key properties of blockchain technology (decentralized consensus, immutability of the records, transparent database, and self-executing environment) are enabling a trusted environment for cooperation and interaction between users who do not trust each other [32]. Based on this fact, researchers have recognized blockchain technology as a solution to the problem of trust between participants in global smart manufacturing networks [6].

The existing networked manufacturing models (not blockchain supported) make significant progress in information and resource sharing. However, the shortcomings of networked manufacturing regarding information and resource sharing are considerable including delays, asynchronous data between multiple parties, multitudes of sharing approaches, irregularity in monitoring mechanisms, and the possibility of shared data being tampered with or concealed. The asymmetric nature of information puts the downstream manufacturers' product quality and credibility at risk. In contrast, due to the properties of the blockchain technology described in the previous section, the blockchain-based approach improves the quality of information sharing, reduces operational costs (due to intermediation), enables dynamic production resource allocation, and enables peer credit evaluation [33]. Therefore, blockchain provides an online environment for enabling decentralized self-organization and thus offloading and accelerating the optimization of upper-level manufacturing planning [34].

In the general blockchain-supported manufacturing model, the blockchain network represents an additional sublayer of the infrastructure layer [35], which supports the establishment of the entire framework by providing the hardware and software infrastructure for the ecosystem (Fig. 2). Blockchain sublayer is structured to support various functions such as manufacturing production, materials and inventory management, smart supply chain, and security and identity management [36]. Blockchain technology provides methods and tools, which include application program interfaces, protocols, and software development kits to support the exchange of data, resources, and knowledge in a transparent, safe, and decentralized way [37]. The Internet of things (IoT) infrastructure of the manufacturing resources is connected directly to the blockchain network through extensible embedded software components [38]. The manufacturing activities in the smart factory are recorded in the blockchain and then retrieved by the enterprise applications for monitoring, planning, and control [36].



ERP - Enterprise Reource Planning, MES - Manufacturing Execution Syste
SCMS - Supply Chain Management System

Fig. 2. *General blockchain-supported manufacturing model*

Smart contracts are employed to write complex data on the blockchain network and to enable the self-execution of automated procedures. Issued smart contracts on the blockchain are containing information on the available time for processing, processing capabilities, and expected compensation for utilization of the manufacturing resources [39]. The personalized manufacturing tasks/demands are published on the smart contracts and each manufacturing service matching between the demander and provider is recorded as a transaction in the blockchain [38]. Furthermore, smart contracts are used to provide membership registration, certification authority, and security and privacy verification [36]. The captured manufacturing data from the sensors/controllers is directly written on the smart contract and consumers who are calling for manufacturing services can verify the capabilities or past actions of providers on the blockchain network [38]. The data written on the transparent and immutable blockchain is signed by the public key of the source, which increases data reliability and trustfulness.

The differences in the concepts presented in the literature on the implementation of blockchain technology in manufacturing systems are mainly twofold, namely: the level at which blockchain technology connects to the manufacturing system is different, and different manufacturing processes are being executed using blockchain technology. In the case of cloud manufacturing, blockchain technology is used only as a storage layer where interactions between providers and consumers are recorded, and the cloud platform still ensures that data is published and classified in the cloud [40]. The manufacturing resources are packed in services, which are then posted on the platform and are not necessarily written on the blockchain. Similarly, individual manufacturers offer their services in the case of social manufacturing (Fig. 3), where the need and supply are advertised in a peer-to-peer (P2P) way via social networks [38]. In the case of Shared manufacturing, individual production units and manufacturing resources are directly connected to the blockchain network and are also interacting with other entities on the blockchain network [41]. The direct connection of individual manufacturing resources results in a high amount of interactions that are written on the blockchain. This in turn means that blockchain-supported Shared manufacturing systems are more dependent on the performance properties of the blockchain technology.

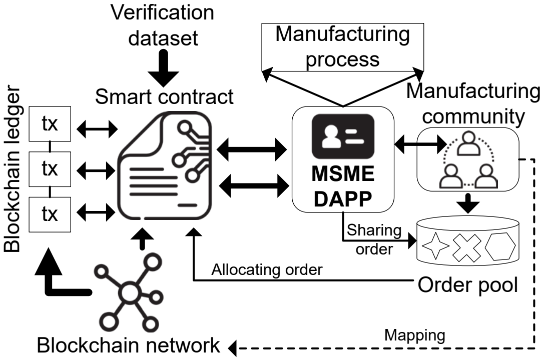


Fig. 3. *The concept of blockchain-supported social manufacturing, adapted from* [42]

2 SCALABILITY SOLUTIONS IN BLOCKCHAIN TECHNOLOGY

Applications built on blockchain technology have in the past encountered limitations of blockchain technology [43]. The main limitations of scalability have severely affected the performance of the applications on the blockchain network and have degraded the user experience. Scalability limitation is the main reason why blockchain technology is not more widely adopted in real-world applications [9]. For this reason, general-purpose solutions for increasing scalability have appeared, which are supposed to solve the scalability problem of blockchain technology. General-purpose solutions represent network organization mechanisms, methods of recording data in the blockchain, and topological upgrades of the blockchain network. For specific applications, the implementation of these solutions is adapted and upgraded according to the characteristics of the applications.

2.1 Scalability Limitations

Nodes in a blockchain network are communicating to update distributed database of data records in a coordinated manner. To update distributed database, each node must store the whole data by itself. New data emerging at one point of the network must propagate through the network and nodes must agree to update records. These properties of the blockchain network are the main reason for the scalability limitations of blockchain technology. The major scalability limitations (Table 2) of the blockchain technology are recognized in transaction throughput, storage size, and read throughput [30].

Table 2. *Scalability limitations of the blockchain technology*

Scalability limitations	Reason	Consequences
Transaction through-put	Information propagation, network synchronization	Congestion of the blockchain network, pending time increases, transaction fee increases
Storage size	The constant growth of the distributed database	Large storage requirements, fewer nodes are able (blockchain) to run a full node
Read through-put	Lack of full nodes in the network, high amount of requests from users	Longer waiting time for requested data

Transaction throughput is the main scalability limitation of blockchain technology as it affects all the users of blockchain technology [29]. Due to the technological limitations of information propagation in the network, blockchain networks cannot confirm new transactions faster in a decentralized way. If we increase the size of the data, being sent through the network the information propagates slower through the network [44]. In addition, the larger the network the longer it takes for the information to propagate through the network. Blockchain networks intentionally increase the period of new transaction confirmation to enable better synchronization of the nodes in the network and thus reduces opportunities for malicious acts [24]. The consequences of limited transaction throughput are congestion of the blockchain networks. When the number of pending transactions exceeds the maximum block size, some of the transactions will have to wait for another block to be included in the blockchain [46]. Such congestion of pending transactions for confirmation causes competition between users for the execution priority of their transactions. Transaction priority increases by higher transaction fees and therefore such blockchain congestions results in an overall increase in transaction fee on the blockchain network [47].

The storage size limitation of blockchain technology emerges due to the constant growth of the blockchain and the fact that each node participating in the confirmation of transactions must keep a complete record of the data on the blockchain [47]. All participating nodes must have large storage capacities at their disposal to ensure the security of the written data on the blockchain. As blockchains are growing, fewer and fewer nodes are capable to store the whole blockchain on its hardware and the decentralization of the network is reducing [48]. Consequently, due to the storage size limitations, many of the nodes in the network are not storing the whole blockchain (are not full nodes) but are storing only parts of the blockchain that are relevant to them (light nodes) [49]. However, when users who do not run blockchain nodes are querying for the data written on the blockchain, light nodes cannot provide all the data. This is the reason for the read-throughput limitation of blockchain technology. The consequences of limited read throughput of the blockchain network are longer data queries and a longer synchronization period for new full nodes joining the network or for nodes who missed a message.

Compared with the centralized payment system like banks, performance (scalability) cannot be improved easily in blockchain, a self-regulating system, that needs more consideration to maintain decentralization [29].

2.2 Scalability Solutions

In response to the problem of scalability, new solutions are being presented that seek to increase the scalability of the blockchain network while maintaining the same degree of decentralization and security. Most of these solutions do not ensure this, but they do enable the change of blockchain properties regarding the trilemma (increase scalability and reduce security or decentralization) according to the requirements of the blockchain network users. Solutions that would allow for greater scalability while maintaining the same level of security and decentralization are mainly solutions based on technological leaps (e.g. quantum computers). One such example is improving the speed of data propagation across the distributed network [50]. By allowing nodes to process and transmit messages faster in a distributed network, new blocks could be confirmed faster or they can be bigger, in an equally secure and decentralized blockchain network.

Other scalability solutions thus in most cases suggest the use of new innovative methods in the implementation of the blockchain network, while with such an approach they merely position the blockchain network properties elsewhere within the trilemma. Some of these solutions even allow for dynamic trilemma positioning. The point is that with the help of these scalability solutions, the trilemma surface can be filled with different properties of blockchain networks, and then users can choose the network that has the appropriate properties, depending on their needs. This work focuses on these types of scalability solutions that result in a change of trilemma properties. They can be divided into solutions that focus on the first layer design of blockchain (L1) and second layer solutions (L2) [51]. Table 3 presents the scalability solutions presented in the literature.

Table 3. *Scalability solutions in blockchain technology*

Solution		What	How
Layer 1	Block data	TT, SS, RT	Block compression, data reduction
	Consensus mechanism	TT, SS, RT	Improved consensus mechanism
	Blockchain structure	TT	Different database structure
	Sharding	TT, SS, RT	Partitioning of the network
Layer 2	Payment channels	TT, SS	Channels offload transactions from the blockchain
	Sidechains	TT, SS, RT	Additional blockchain network connected to the main network
	Cross-chain	TT, SS, RT	Multiple connected blockchain networks

TT - transaction throughput, SS - storage size, RT - read throughput

L1 solutions include optimizing the process of block generation, consensus mechanisms, and blockchain structure. L2 solutions focus on relieving the main blockchain network by performing part of the transactions from the blockchain network or by transferring part of computationally demanding tasks to platforms that are not set on blockchain networks. First L1 solutions were optimizing the size of the block in the blockchain. Block compression and data reduction are used in this kind of scalability solution to increase transaction throughput. Segregated witness (SegWit) is one implementation of this solution, where transactions are split into two segments [52]. The unlocking signature is removed from the block creating more space for other transactions to be added to the same block. Various solutions related to block compression have been also proposed (e.g. Txilm [53]). The idea is to reduce some redundant data of a block that has been already stored in the Mempool of receivers [29].

L1 scalability solutions also optimize consensus mechanisms in the blockchain network. Many different mechanisms have been proposed and the main difference is usually regarding the process of candidate selection for block creation or in the process of block acceptance in the blockchain. The first consensus mechanism proposed in the bitcoin network was proof of work (PoW) [54]. Compared to pow, an example of alternative consensus mechanism proof of stake (PoS) avoids the computational overhead in the process of candidate selection for block creation. The basic idea of PoS is that nodes with more currencies in the system are less likely harm the system and therefore candidate selection is done based on the owned funds in the blockchain network [55]. Delegated PoS extends the idea, that stake is used for voting of delegation nodes that are fulfilling technological requirements (enough storage and computational power) [56]. Only delegated nodes are participating in transaction confirmation and only they are storing the whole blockchain. Therefore, communicational overhead in the network is reduced as well as storage requirements are justified. Practical Byzantine fault tolerance (PBFT) is another voting-based consensus mechanism [57]. It reduces the complexity of consensus to the polynomial level but requires more communication overhead. Due to the overhead, the PBFT works efficiently only when the number of nodes in the distributed network is small. For that reason, usually only selected nodes in the network are a part of the transaction confirmation process.

Transactions in a traditional blockchain network are written in blocks that are organized in a single chain. To enable concurrent block generation a different blockchain structure has been proposed. An example of a different blockchain structure is the directed acyclic graph (DAG). In the case of DAG, several blocks can be connected to a previous block. This results in a parallel creation of blocks which increases transaction throughput. As opposed to traditional blockchain technology where dedicated validators must exist to generate and order blocks, transaction ordering in DAG is done asynchronously by the account owner in charge of the ordering. A transaction is valid if the majority votes are in favor of that transaction. Storage limitations are not omitted by this kind of scalability solution [58].

The idea of the sharding scalability solution is to divide the blockchain network into several smaller networks that process transactions internally, however, all shards are connected in a larger network [7]. Validators in each shard only need to process a small part of arriving transactions and different shards can process transactions in parallel. This results in higher transaction throughput, transaction confirmators are relieved of storing the whole blockchain and reading throughput is increased [59]. On the other side, cross-shard transactions cause communication overhead and increase confirmation latency.

First L2 solutions appeared in the form of payment channels, in which a temporary off-chain trading channel is established. Any number of transactions between participants is performed via the private channel. If participants want to close the payment channel at any point, they can broadcast the most recent signed transaction message to the blockchain network to finalize their transfer of funds [51]. Therefore, multiple transactions can be executed on parallel channels, and only final states are written on the blockchain, which results in better transaction throughput and reduces storage requirements.

Another L2 solution is sidechains, which are separate blockchain networks that are pegged to the main blockchain (mainchain). Funds can be freely transferred from the mainchain to the sidechain and vice versa. The first concept of sidechains was proposed in 2014 [60]. The concept defined a general notion of a 2-way peg and described two operational modes of interactions between pegged chains – asynchronous and synchronous. The asynchronous mode assumes that the mainchain is agnostic to all sidechains, but it is necessary to rely on sidechain validators in the process of validating transfer transactions between chains. One of the sidechain solutions that enables asynchronous mode is Plasma [61] on the Ethereum network, which acts as the mainchain. ZK-Rollup is another technology, which enables the construction of sidechains. ZK-Rollups bundle hundreds of transfers on the sidechain into one transaction on the mainchain by employing the cryptographic tool of zero-knowledge proofs [62]. Synchronous mode assumes that the mainchain and sidechain are aware of each other's existence and can directly verify the validity of transfer transactions between chains. This concept is further explored in cross-chain scalability solutions where two separate blockchain networks can be connected with cross-chain transactions, however, both networks can operate even if the connection is cut between blockchains. One implementation of the cross-chain scalability solutions is the Polkadot ecosystem [63]. Both of the scalability solutions are improving transactional throughput, storage limitations, and read throughput by dividing blockchain network into smaller networks, which enables better information propagation. In addition, less strict requirements are posed to nodes who participate in the transaction confirmation process.

Off-chain solutions exploit the possibility to relay computational or storage tasks to capacities or networks that are not organized as a blockchain network. A multi-party computation network or distributed data storage network such as is InterPlanetary File System (IPFS) [64] can be employed as an off-chain solution. A distributed hash table (DHT) is used to store blockchain raw data on an off-chain data storage while the hash of the raw data is stored on the blockchain. There are different protocols, which define what part of the computation is done off-chain and how computation is organized. Truebit is an example of a system that outsources complex computing tasks to an off-chain market [65].

3 SCALABILITY SOLUTIONS IN BLOCKCHAIN-SUPPORTED MANUFACTURING

Given the features of blockchain-supported manufacturing systems, it seems inevitable that such large global systems will eventually encounter a limit to the scalability of blockchain technology. Scalability solutions enable blockchain technology to be a trust-ensuring solution among users in large-scale systems. Due to the high volume of the presented scalability solutions in the literature, this paper focuses on the implementations of scalability solutions in the presented blockchain-supported manufacturing concepts in literature. This section discusses in detail how are general-purpose scalability solutions applied and modified for specific problems in the field of manufacturing.

3.1 Methodology

A literature search was conducted in the Google Scholar database, where a broad range of literature on blockchain-supported smart manufacturing can be identified. The searches were conducted using the following keywords in all possible combinations: blockchain, manufacture (ing), scalability, and scalability trilemma. Review articles were omitted from the analysis. The focus was on works that are aware of the limitations of scalability of blockchain technology (works that do not address scalability were omitted).

The selected literature was arranged according to the type of scalability solutions mentioned in connection with the limitation of the scalability of blockchain technology. Further identification of whether the concept is designed specifically for any of the specific paradigms of smart manufacturing (e.g. cloud manufacturing) or just for general manufacturing systems was made. Then assessments were made to what extent scalability limitations and the proposed solution was described in each of the screened papers. The evaluation criteria divided literature into three categories.

1. category: Articles that merely identify the scalability limitations of the blockchain technology and suggest one of the general-purpose solutions as potential (citing other literature) in connection with the proposed concept.

2. category: Papers that in addition to stating the solution, also explain in more detail why this selection is justified according to the proposed concept. The implementation of a scalability solution in a manufacturing environment is more clearly defined (e.g. discussing how manufacturing-specific properties affect the integration of the scalability solution in the concept).

3. category: Literature that describes in detail how this solution would be included in the proposed concept, and may even further adapt the proposed scalability solution according to the proposed concept. The papers in the third category extend general-purpose scalability solutions with manufacturing-specific functionalities.

Table 4. *Literature classification according to the scalability solution*

Scalability solutions		In manufacturing
Layer 1	Block data	[66], [67]
	Consensus mechanism	[68], [69], [70], [71], [72], [73], [74], [75], [67], [76]
	Blockchain structure	[77], [78], [79], [80], [81], [53], [82]
	Sharding	[83], [84], [85]
Layer 2	Payment channels	[86], [87]
	Sidechains	[41], [88]
	Cross-chain	[89], [90], [91], [92], [93], [94], [69], [70]
	Off-chain	[71], [95], [96], [97], [98], [99]

3.2 Selected Literature

According to the described methodology, 36 papers were found in the literature that addresses the problem of scalability in blockchain-supported manufacturing and suggests one of the scalability solutions. Table 4 shows the reviewed literature, which is classified according to the type of considered scalability solution in connection with the manufacturing system. First L1 scalability solutions in blockchain-supported manufacturing are presented and analyzed. Most concepts are proposing the improvement of the consensus mechanism and blockchain structure, where mainly alternatives to the PoW consensus mechanism are modified for specific use in manufacturing, and the DAG structure in connection with IoT devices is discussed. Then L2 scalability solutions are presented and analyzed. Most authors are proposing off-chain solutions and cross-chain solutions where the IPFS approach is the most common one and different relay protocols for cross-chain interactions are second.

Fig. 4 shows a comparison between the emergence of literature in the field of scalable solutions in blockchain technology and the field of blockchain-supported manufacturing over time. The figure shows that the literature in the field of blockchain-supported manufacturing does not exactly follow the trend in the field of blockchain technology. There can be several reasons for this. It may mean that researchers in the field of smart manufacturing are unaware of the importance of the scalability limitation of blockchain technology. One of the explanations may be that the solution used in the global manufacturing system has not yet been implemented and that this limitation of scalability has not yet been observed in the existing manufacturing system. In the case of Bitcoin, which is the world's first blockchain network, scalability limitations have been identified after several years of operation.

Another possible explanation is that researchers in the field of smart manufacturing simply assume that the operation of blockchain technology will be perfected in the future and that such systems will come to life when the technology is ready for it. Until then they leave the solution to the scalability problem to researchers in the field of blockchain. However, because of the trilemma, we see that this limitation will always exist and it is necessary to explore what properties of the blockchain network regarding the trilemma are beneficial for the manufacturing system.

The reviewed literature was also divided into three categories according to the criteria described above. Fig. 5 shows the proportions of literature according to the assessed extent of addressing the problem. Almost half of the reviewed literature belongs to the second category, and the least literature belongs to the first category. The latter is surprising, as the word blockchain has been of interest to publications in recent years, and as a result, quite a bit of lower-quality literature has been published. Thus, the literature prevails, in which the authors have a good understanding of the problem of scalability of blockchain technology and, consequently, the concepts are well described. However, most of the papers struggle to present manufacturing-specific solutions and are sometimes exploiting the concept of blockchain-supported manufacturing to present general-purpose scalability solutions. Fig. 5 also shows a graph showing how the extent of addressing the problem in the reviewed literature changes over time. There is a growing number of literature in time that describes the use of scalability solutions in blockchain-supported manufacturing in dept and with a lot of effort.

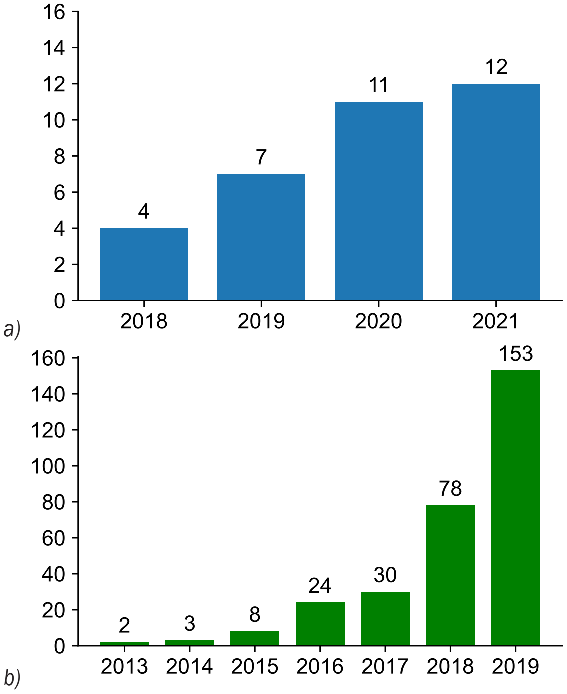


Fig. 4. *Emergence of literature in time; a) scalability solutions in blockchain-supported manufacturing; and b) scalability solutions in blockchain technology, adapted from* [30]

3.3 Reviewed Solutions

In the next subsections, reviewed literature is presented in detail for each group of scalability solutions and manufacturing-specific properties are highlighted for each solution.

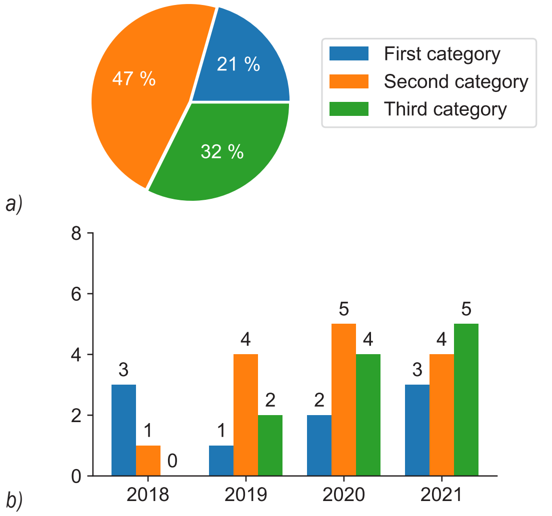


Fig. 5. *a) Proportions of reviewed literature quality; and b) extent of addressing scalability problem in time*

3.3.1 Block Data

In the case of the L1 solutions related to block data optimization, two solutions related to manufacturing have been presented so far. The first proposes to upgrade the Merkle Patricia tree (MPT) specifically for IIoT devices in SMS **[66]**. The new approach optimizes the storage mode of the blockchain and accelerates the speed of the data query. The solution also supports thread-safe and parallel data operations, speed up block verification or construction, and further improves the transaction throughput. A tree structure called the concurrent Merkle-Patricia tree, which supports concurrent insertion and lock-free search, is a general scalability solution that can be applied to any blockchain-based system with many blockchain queries and high data volume scenarios. In the paper, the solution is used to expand traditional blockchain so that, via limited hash computing, it can rapidly locate the manufacturing equipment or products from intelligent manufacturing systems. The second concept is trying to optimize the blockchain settings (block size, block interval, selection of the block producers) using the deep reinforced learning (DRL) technique **[67]**. A deep reinforcement learning approach is adopted to handle the dynamic and large-dimensional characteristics of the IIoT systems. For optimization, this solution takes into account the trade-off defined by the scalability trilemma. The authors proposed metrics that, in their opinion, should characterize the blockchain network's scalability, decentralization, and security. The presented design of a modulable blockchain where properties of the blockchain are adjusted using DRL is well adapted to the dynamics of the manufacturing systems. However, the presented solution is general purpose and can be used also on other blockchain-based applications (e.g. any blockchain network can apply presented a framework to improve performance).

3.3.2 Consensus Mechanism

The above-described concept also optimizes the choice of consensus mechanism, so it is also included in the group of solutions that use the improved consensus mechanism as a scalability solution. Another solution has been presented in the literature that similarly optimizes the consensus algorithm of blockchain-supported manufacturing using deep reinforcement learning **[75]**. This solution is only optimizing the selection process of the validator in terms of performance and the trilemma is not taken into account in terms of decentralization and security. The proposed deep reinforcement consensus mechanism is trained by a DRL training set and is adapted to the smart manufacturing business model. Applying the DRL-optimized consensus mechanism to manufacturing based on an IoT environment generates simpler operations, faster response, and higher accuracy and security than the traditional consensus mechanism. However, the presented approach did not take into account any specific properties of manufacturing systems that would affect the design of the consensus mechanism. This approach can be used in any kind of blockchain-based application where optimization of blockchain scalability is necessary.

Most of the other concepts that include consensus mechanism solutions, suggest the use of an alternative consensus mechanism as implemented in the case of the bitcoin network PoW. A blockchain architecture that uses a dynamic PoW consensus with a block checkpoint mechanism for IIoT was proposed **[72]**. The dynamic PoW consensus mechanism upgrades the traditional PoW mechanism by introducing a sliding window algorithm, which defines how many preceding blocks need to be included in the newly mined block. The authors also discussed the security aspect of the proposed more scalable consensus mechanism. The consensus offers different mining difficulty levels for different transaction arrival rates of IIoT devices, while the checkpoints define how to generate the next block hash. Instead of constant mining difficulty, the solution introduces four different levels (Table 5) where each level is triggered for a certain rate of incoming communication traffic generated by the IIoT devices. The authors have shown that for low arrival rates, the security is high, while for high arrival rates, the throughput is high, which makes the proposed protocol scalable to meet the high concurrency and security requirements of blockchain-supported IoT manufacturing networks.

Table 5. *Difficulty levels in the DPoW consensus mechanism, adapted from* **[72]**

	Tx arrival rate	Difficulty	Size (bits)	Target hash
1	High	Level 01	4	SHA256[0:1]
2	Medium-high	Level 02	8	SHA256[0:2]
3	Medium-low	Level 03	12	SHA256[0:3]
4	Low	Level 04	16	SHA256[0:4]

The proposed concept of a decentralized manufacturing network addressed a comparison of performance between PoW and the proof-of-authority (PoA) consensus mechanisms [68]. The proposed PoA consensus mechanism implements a general-purpose PoA consensus mechanism named Clique. The authors emphasize that a different type of consensus mechanism is appropriate for different uses. They highlight the better decentralization and security features of the PoW mechanism compared to bad scalability as it is in line with the scalability trilemma. The authors discuss that the PoW mechanism would be more appropriate in the case of provenance tracking across a large supply chain, which requires higher trust and security. However, if a blockchain system is implemented for the verification of machine states such as states of the computer numerical control (CNC) machine, the PoA will be sufficient. The proposed solution does not provide any additional manufacturing-specific insights on how different consensus mechanism affects the integration into the manufacturing system.

A consortium PoA consensus mechanism is proposed in the case of the smart contract platform for the machine servitization blockchain network [71]. The proposed system of three-dimensional (3D) printing servitization is not public and it is a system provided by a known platform provider to known machine providers. Therefore, there is no need for a public network. The employed PoA consensus mechanism is a general PoA mechanism (not manufacturing specific) where only a set of known trusted entities is allowed to set up confirmation nodes. It supports arbitrary block times and sizes, increasing network performance and decreasing transaction latency. A free transaction environment is an important feature of PoA that is especially valuable for manufacturing use cases. This means that the gas price is set to zero, and the blockchain network imposes no transaction costs. Another benefit of free transactions is that the native cryptocurrency can now be easily used for manufacturing service payments. The currency can serve as a voucher (namely an Ethereum Request for Comment (ERC) token without smart contracts), and its value can be mapped to FIAT at a fixed price. PoA consensus mechanism was also selected in the case of the proposed architecture for fast certification of manufacturing data, compatible with current industrial landscapes [76]. A general-purpose PoA consensus mechanism is employed due to the permissioned nature of the certification system. There are two types of nodes, namely administrator nodes and mining nodes. Administrator nodes are reserved for the sovereign entity that fundamentally holds legislative power over the network. Mining nodes are responsible for creating (mine) blocks and can be deployed across multiple cells in a production line, different production lines, departments, factories, or even organizations.

A consensus mechanism that supports a permissioned blockchain network was proposed to satisfy scalability requirements regarding the ISA95 compliance of SMS [69]. The ISA95-CTS and SMS ecosystem constitute a broad scope of devices and systems with varying computational capabilities where scalability becomes a crucial design requirement. The reference architecture design specification requires 300 ms maximum latency with a throughput of 6000 to 8000 transactions per second (TPS). These requirements can be met with a permissioned blockchain network employing a trivial consensus protocol Raft, which is a general-purpose blockchain consensus mechanism. A similar proposal of permissioned blockchain architecture was presented regarding the manufacturing blockchain of things concept. The authors have suggested the use of a simple crash fault-tolerant (CFT) consensus protocol to achieve higher throughput and lower latency [74]. The proposed CFT protocol is also a general-purpose consensus mechanism that can be employed in blockchain networks for arbitrary use cases.

Two concepts in the literature suggest the use of the practical Byzantine fault tolerance (PBFT) consensus mechanism, stating that it has better performance than the traditional blockchain network (e.g. Ethereum) [70], and [73]. However, the proposed concepts are not considering the deterioration of privacy and decentralization in the system according to the scalability trilemma. PBFT consensus mechanism is a general-purpose blockchain consensus mechanism that is already employed in other general blockchain networks (e.g. Hyperledger). None of the concepts are extending the solution according to the requirements of manufacturing systems. For example, the authors recognize that stability of the throughput (fluctuation) is one of the problems of the PBFT mechanism, which can severely affect the processes in manufacturing planning that require synchronization. However, the proposed solutions do not provide any solution which would mitigate this manufacturing-specific problem.

3.3.3 *Blockchain Structure*

All the concepts that implement blockchain structure scalability solutions with blockchain-supported manufacturing are based on the use of DAG structure, with the implementation on the IOTA network being the most prominent. In four cases [77], [79], [53], and [78], this technology is only mentioned as a way to improve the scalability limitations of blockchain technology in connection with manufacturing. In all four concepts of blockchain-supported manufacturing is a physical layer directly connected to the blockchain network and the authors are expecting a high number of activities and interactions between entities that would require high transactional throughput. One of the concepts presents the implementation of the proposed architecture using STM32 IoT devices. The scalability evaluation of the implemented system suggests improved scalability and that the proposed architecture is feasible in SMS [82]. However, all of the above concepts do not provide any specific details on how a general-purpose DAG blockchain structure would be implemented in connection with the manufacturing system.

Some authors have described in more detail the implementation of the masked authentication messaging (MAM) protocol defined by the IOTA network in the case of communication between IIoT devices in SMS [80] and [81]. In the case of blockchain-supported cloud manufacturing the MAM, communication protocol is employed to realize flexible data access management [81]. The restricted mode of privacy and encryption is proposed for data sharing to control the visibility and access of a channel. Besides connections between entities in form of contracts (smart contracts), the DAG blockchain structure provides an infrastructure for an additional data layer. The data layer provides information for participants in the system with variable frequencies and does not require previous agreements or data access. MAM communication channel can regularly deliver information about relevant key performance indicators of cloud manufacturing, by the previously required constraints. In the system architecture of smart factories, which requires real-time data collection, the DAG structured blockchain is employed for a distributed traceability system and the MAM protocol enables a communication channel [79]. Each device in the smart factory is capable of publishing its messages and broadcasting them to other machines. MAM protocol is modified to enable different types of complex tree-like workflows of manufacturing processes. The modified protocol enables channels to merge and backtrace paths, which is important as multiple assembly lines merge leads to channel switching issues and source traceback is important for traceability.

In none of the above describes concepts the authors do not consider the limitation of the trilemma. Security problems and poor decentralization of the IOTA network [100] have already been identified in the literature, which may suggest that this technology is not optimal in the case of global SMS.

3.3.4 *Sharding*

Concepts that include sharding as a scalability solution describe the implementation of the sharding mechanism in SMS in much more detail. One of the solutions is not implementing a strict sharding mechanism but scalability is improved in a similar matter. A clustering algorithm has been used to group the overlay network participants into clusters and that results in low latency, and higher throughput [83]. The participating nodes of the clusters also select a cluster header as well as a co-leader of the cluster in the case the cluster header becomes malicious or leaves the network due to a sudden loss of connectivity. These cluster heads are responsible to maintain and manage the blockchain-supported overlay network of the manufacturing system. The industrial production line is equipped with randomly placed IIoT-enabled machines and devices. Such an unstructured environment creates overlapping network topology, which is not suitable. The proposed algorithm in a distributed manner discovers network nodes by exploiting local network topology knowledge and forms clusters in random geometric graphs. This facilitates covering the whole network with a minimum number of nodes and further reduces processing and packet overhead on IoT devices.

Another concept proposes a sharding hashgraph consensus mechanism (Fig. 6) and introduces a node evaluation mechanism based on the state of the node, which is applied to divide a large number of nodes into many shards dynamically [85]. This mechanism comprehensively considers the node's geographic location, credit score, network status, and CPU resources and divides all nodes in the network into multiple shards. The nodes in each shard are geographically close, the network status is generally good, and the credit rating is similar. Each full node is responsible for a group of lightweight IIoT devices (sensor network) in a certain area, receiving all data uploaded by the sensor network and storing these data. The simulation results demonstrate that the proposed algorithm demonstrates better scalability performance in comparison to the PBFT consensus mechanism. Both of the described sharding solutions are considering the low capabilities of the IIoT devices in manufacturing networks, which are the end users in the blockchain network, and are proposing solutions that would increase the scalability of the blockchain network specific for blockchain-supported manufacturing.

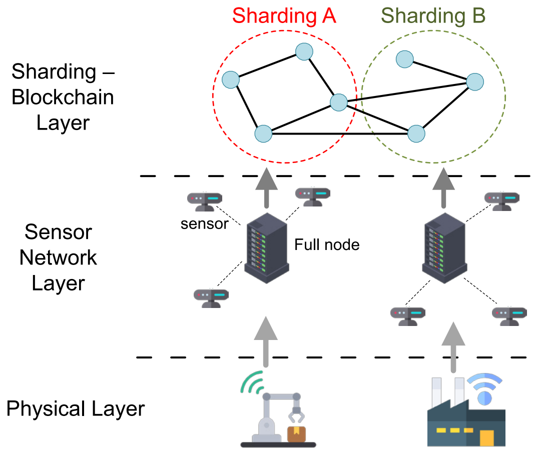


Fig. 6. *The IIoT data management system architecture based on blockchain and sharding, adapted from* [85]

However, the effectiveness of sharding is still challenging due to the uneven distribution of malicious nodes, Fig. 7. In IIoT user data and computing tasks are generally transferred to edge nodes (EN) from user equipment (UE) using distributed units (DU). A UE is set in a harsh environment for a long time and it is impossible to ensure that the task to be migrated for each device has not been tampered with. The blockchain technology approach prevents tampering with computing tasks across the entire network. The blockchain nodes are composed of all UE and DU. The UE layer consists of ordinary nodes, and the DU layer contains consensus nodes. Potential malicious consensus nodes can tamper with the data, causing excessive computing overhead and even paralysis of the IIoT.

The authors in their paper assume that each attacked UE will send the wrong calculation task to the DU. Therefore, a many-objective optimization algorithm based on the dynamic reward and penalty mechanism has been proposed to optimize the shard validation validity model [84]. The dynamic reward and penalty mechanism dynamically combine the diversity function and the convergence function to increase the selection pressure and make the population closer to the real Pareto frontier (PF). At the same time, the weights of the two functions are dynamically set to classify individuals in the population, thereby making individuals with different performances evolve iteratively. The proposed optimization algorithm is general-purpose and can be applied to any sharding solution in the general-purpose blockchain network. However, the possibility for malicious nodes seems to be greater in the case of IIoT networks due to a large number of devices with limited capabilities and the high impact (the whole manufacturing system can be obstructed) of such malicious attacks. The presented sharding solutions mention the limitation of the scalability trilemma but do not provide any discussion or analysis of how the proposed concepts would affect the relationship between scalability, decentralization, and security in blockchain-supported manufacturing.

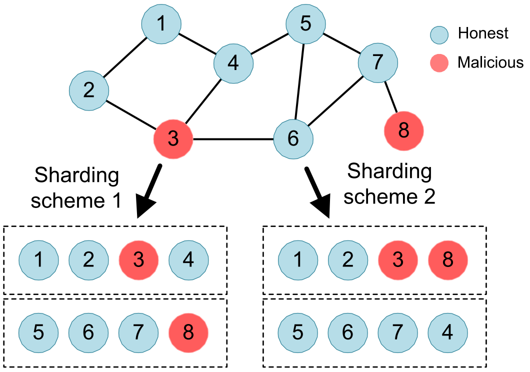


Fig. 7. *Sharding scheme leads to the aggregation of malicious nodes, adapted from* [84]

3.3.5 Payment Channels

Payment channels in blockchain-supported manufacturing are poorly addressed. Only in two concepts, are payment channels proposed as one of the possible scalability solutions. In the proposed blockchain protocol for manufacturing and supply chain management of integrated circuits, the authors have recognized the scalability limitations of blockchain technology and they have also proposed possible scalability solutions to be implemented in the concept [86]. The implementation of the state channel was described in three parts. First, a part of the blockchain would be locked and updates can be made if a specific set of participants agrees to it. Second, the participants update themselves by constructing and signing transactions without submitting them to the blockchain network. Third, participants would submit the final state to the blockchain network after the interactions are finished to close the channel.

Payment channels in the form of a lightning network were proposed similarly in the blockchain model for industrial internet [87]. For low transaction speed, a lightning network could process high-frequency but small-sum transactions in an off-chain way. However, none of the above works provides any kind of detailed explanation of how this scalability solution would be connected to the manufacturing systems. The lack of interest in this L2 solution is probably because other L2 solutions provide better functionality and interoperability of the system. Both of the papers addressing payment channels were written in 2018 when other L2 solutions were still being explored and developed.

3.3.6 *Sidechains*

In contrast to the payment channels, the literature discusses the L2 solution of sidechains and blockchain-supported manufacturing in more detail. Both of the concepts are proposed for a specific type of SMS, namely Cognitive manufacturing and Shared manufacturing. The first paper proposes a topic mining process in blockchain-network-based cognitive manufacturing [88]. The proposed method exploits the highly universal Fourier transform algorithm to analyze the context information of equipment and human body motion based on a variety of sensor input information in the cognitive manufacturing process. Because of its primitive management, a cognitive manufacturing process can have problems including the absence of efficient statistical information, negligence of supervision, and inconsistency of physical and soft data. The conventional physical Cognitive manufacturing system has unclear information in the manufacturing process, whereas the proposed cognitive manufacturing process supports end-to-end trace based on the transaction data saved in the blockchain in order to prevent data loss in each step. The blockchain-supported cognitive manufacturing process exploits the information exchange of the data collected in real-time to analyze a variety of data related to the traceability system, extension infrastructure in each base, and worker's work system. Such an approach in manufacturing results in the collection of massive amounts of data. Because of the structural problem of the blockchain (scalability limitations), it is difficult to include massive data on the general-purpose blockchain. Therefore, sidechains are used to store a large amount of data collected by smart devices in the system. The mapping between the specific data on the sidechain and the mainchain is done by writing the hash of the block on the mainchain. However, the proposed solution employs general-purpose sidechains and does not provide any specific reason why another scalability solution is not viable to provide better scalability in the case of blockchain-supported cognitive manufacturing.

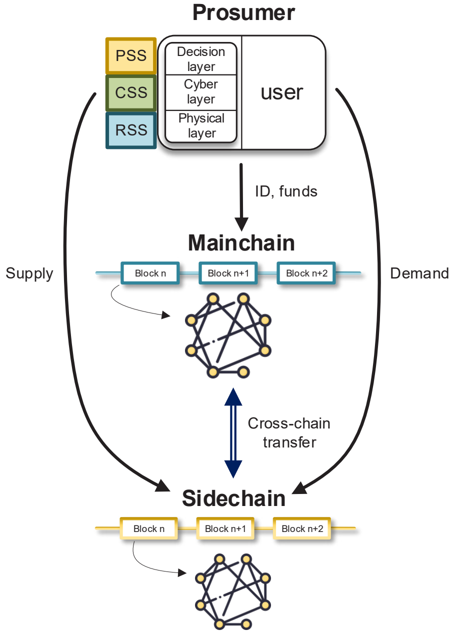


Fig. 8. *Sidechain solution in blockchain-supported manufacturing, adapted from* [42]

The second paper presents a scalable framework for blockchain-supported Shared manufacturing (Fig. 8) that preserves the transparency and immutability characteristics of transaction records, which is critical to building trust between entities in blockchain-supported systems [41]. The concept proposes that authentications of the manufacturing resources in the system are done on the mainchain and all the interactions between providers and consumers of the manufacturing services are done on the sidechains. The authors further discuss what cross-chain technology should be used to relay data from sidechains to the mainchain, and a hybrid solution is proposed. It allows a more configurable setup of sidechain networks, which means that it can provide greater scalability and interoperability according to users' needs. When users determine that they need a blockchain network with different properties, they can open a new network (sidechain) with custom settings or connect an existing network with a preferred setting. There are two types of connection between blockchains in the proposed concept, namely information and financial. Financial is provided by the general-purpose sidechains scalability solutions. The information connection is provided by the appropriate implementation of the proposed protocol using smart contracts both on the sidechains and on the mainchain. Upon entering the system on the mainchain, prosumers create a digital identity with which they then carry out transactions on various blockchain networks. Thus, prosumers can track other prosumers throughout the tree of sidechains and obtain information about their business history, and use this information when deciding to do business with a particular prosumer. The authors also discuss that sidechain networks would be organized by manufacturers in the system who have computer hardware and resources to support this kind of system that benefits them. They compare implementations of the proposed framework on the main public blockchain network and sidechain network, which results in better scalability by the sidechain solution.

3.3.7 Cross-Chain

Cross-chain scalability solutions present variable cross-chain protocols to relay data between two blockchain networks and many of them were connected to blockchain-supported manufacturing. A concept for enabling the traceability of manufacturing processes was presented, where manufacturing products are represented by non-fungible tokens on the blockchain network [89]. In order to reduce the overhead involved, a lightweight contract is implemented as an alternative to the more general ERC-721 compliant version. The authors are further aware of the scalability limitations of blockchain technology, therefore, they propose the use of scalability solutions. The tests on the implemented system showed that varying batch sizes of manufacturing products influence the system's scalability in terms of throughput, ledger size, and potential gas costs. Consequently, small batch sizes, as required for tracing single goods, negatively affect the system's performance. The authors propose cross-chain solutions over L1 solutions because cross-chain solutions provide better interoperability, which is required in the case of the proposed concept. The authors argue that the intersection of industries and bidirectional dependencies requires different environments that should be connected. However, only general-purpose existing cross-chain scalability solutions are proposed, without further explanation of how the proposed concept should be integrated with cross-chain solutions.

Manual asset exchange as a cross-chain protocol is selected in the concept of the infrastructure of decentralized collaborative manufacturing [93]. To satisfy high-performance requirements, the matching layer relies on atomic swaps to enable automatic pricing. The protocol allows the trade of arbitrary crypto-assets, like cryptocurrencies (value tokens) and ERC-20 tokens (capacity tokens) through different blockchain networks. Free capacities of manufacturing machines in the system correspond to a number of capacity tokens on the token layer. However, the cross-chain scalability solution in this concept is an existing general-purpose solution for transferring funds over any general-purpose blockchain network. No additional insights are provided on how manufacturing-specific properties of collaborative manufacturing affect the integration of the proposed scalability solution into the system.

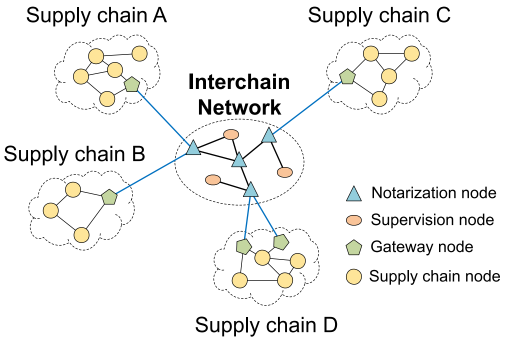


Fig. 9. *Cross-chain architecture for manufacturing supply chain system, adapted from* [90]

Another concept presents a design scheme of an integrated platform for information exchange services provided by participants in a manufacturing supply chain based on blockchain technology [90]. In order to reduce the scalability limitations of blockchain technology and due to the requirements of the global manufacturing supply chain, cross-chain architecture is proposed. An interaction chain is defined as the coordinator in the system and the notary scheme is selected as the cross-chain protocol between different blockchain networks. An interaction chain is managed by authorities and is organized like other blockchain networks. The nodes in the interaction chain are notarization nodes that are ensuring cross-chain communication and global consensus between different networks (Fig. 9). There are four types of nodes in the system. Supply chain nodes are taking care of executing supply chain services. Gateway nodes are in charge of collecting cross-chain transactions and transmitting them to the interaction chain to be verified. Notarization nodes are the nodes implementing notary schemes to validate cross-chain transactions. Supervision nodes are operated by the authorities and are in charge of monitoring the notarization nodes.

A notary scheme is the selected cross-chain protocol also in the algorithm for the blockchain-supported system on multi-chain storage for cyber, physical, and social (CPS) under edge cloud computing [91]. Blockchain-supported CPS systems are generating a huge amount of similar data that occupies the storage of the devices in the system. In addition, the traditional blockchain approach without scalability solutions leads to the mismatch between the communication speed of nodes and the requirements of high concurrency and high response speed in CPS. Data storage and parallel processing become the key factors that restrict system performance. The algorithm divides nodes of the system into separate blockchain networks according to the relationship of communication tightness. A partitioning algorithm based on node community clustering minimizes time for cross-chain communication, resulting in improved speed of data processing and reduced communication load in the system. A similar approach can be employed in other blockchain-supported applications where storage and communication limitations are the main problem.

The above-presented concepts are well presented, however, none of them are discussing how the improved scalability of the system will affect the property of security and decentralization. The trilemma is discussed in a proposed cross-chain protocol of interoperable blockchains for collaborative manufacturing [92]. Existing cross-chain protocols are being extended using a trusted execution environment to increase the security of the solution. A relay scheme is proposed as a cross-chain communication technology. The authors have shown that negligible additional communicational overhead emerges due to the cross-chain interaction, however, security and interoperability are increased.

3.3.8 Off-Chain

Most blockchain-supported manufacturing concepts involve huge amounts of captured data and cannot be stored all on one network, so data storage on a distributed storage system that is not part of the blockchain (off-chain) appears to be the main solution to this problem. The proposed solutions define which data is written on the blockchain and which is off-chain. In the case of the industrial blockchain-supported framework for product lifecycle management (PLM) in Industry 4.0, the authors suggest that some raw data is written off-chain, whereas the hash of raw data is on the blockchain [70]. PLM aims to seamlessly manage all product information, and knowledge generated throughout the product lifecycle for achieving business competitiveness. The information of PLM is difficult to be integrated and shared among the cooperating parties due to the amount of data and privacy reasons. The authors propose that design schemes and certificates are written off-chain, however, manufacturing quality information, recall data, and supply chain traceability data are written on the blockchain (Table 6). Off-chain data is stored in the cloud storage environment, which is employed also for data validation, data cleaning, and data broadcasting.

A similar way of recording generated data is presented in the case of 3D printing as a service in a decentralized manufacturing concept where important data about the service is written on the blockchain network, and additional digital content, such as stereolithography (STL) files, is stored off-chain [71]. The off-chain cloud storage is an add-on integrated into the on-chain logic. The authors define the data and event models for a hybrid on-chain and off-chain decentralized application. On blockchain are stored JavaScript object notation (JSON) structures with hash values, uniform resource locators (URLs), and metadata. URLs are pointing to the 3D printing specification in STL files that are stored off-chain.

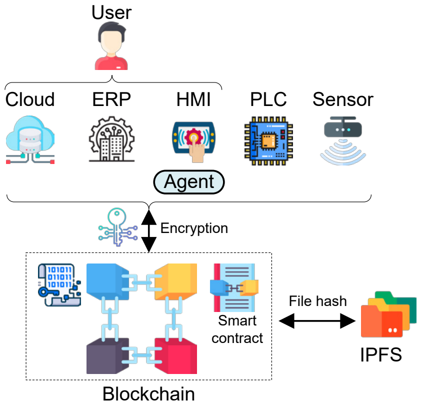
Table 6. *Data in the industrial blockchain-supported framework for PLM, adapted from* [70]

Data type	Privacy	Amount	On or off-chain
Design schemes	High	Medium	Off-chain
Quality information	Medium	High	On-chain
Logistics traceability	Low	High	On-chain
Recall data	Low	High	On-chain
Contracts	Null	Medium	On-chain
Certificates	Low	Low	Off-chain

The data sharing framework for IIoT was presented in the literature, where the authors propose an off-chain procedure for participants to compress and encrypt product data before being submitted to the blockchain [99]. The concept proposes two types of transactions named point transactions and data transactions. Point transactions are indicating the place of the written data on the off-chain and data transactions store encrypted data on the blockchain. When a product id is processed through a path of participants, each of them transfers its product record to a dedicated participant for compression. The dedicated participant then encrypts the compressed product data with a policy and submits it to the blockchain. In the off-chain procedure, participants transferring product records also submit point transactions to store the off-chain storage address of the data of id. At the end of the procedure, the dedicated participant submits a data transaction to carry the encrypted compressed data of the id. To access the data of the id, a data user can send a request to the blockchain. If a point transaction is returned, the user extracts the off-chain address from it and interrogates a certain participant according to the address. The participant encrypts the data of the id with a policy and returns the ciphertext. The user then decrypts the ciphertext according to the policy to acquire the data of the id. If a data transaction is returned, the user directly extracts the encrypted product data from it and decrypts it according to the policy to acquire the data of id. The evaluation results show that compared with the baseline approach, the proposed concept achieves a 4 to 9 times improvement in storage efficiency and a 5 to 20 times improvement in data access efficiency, respectively.

Several solutions suggest using the inter-planetary file system (IPFS) as a distributed storage system. In the case of traceability and management in additive manufacturing systems, IPFS is used to store design files, IoT device records and additional product specifications [94]. When a customer submits an order, the smart contract connects to the product manufacturer and the 3D printing workshop. Once the product manufacturer and the 3D printing workshop confirm accepting the order, the product designer is in a heterogeneous environment with many actors. Thereby, the IPFS-based enterprise file share should be protected from unauthorized users. The authors propose OAuth, Security Assertion Markup Language, Kerberos-based single sign-on (SSO), and authentication schemas to preserve privacy.

Excessive data gathered to satisfy the requirements of the ISA95 standard must also be relayed through the IPFS to reduce the amount of data being written on the blockchain [69]. Various actors in the system can directly read and write to IPFS via P2P network protocols, given that relevant access rights are granted (Fig. 10). The suggested policy can define thresholds, and if a file or transaction content is above the limit, then the blockchain operating system makes the actor write the file content to IPFS. Next, the file hash (acting as the pointer to the original file) is generated and inserted as a new block content to the blockchain. When an actor needs to access the file, first gets the file address on IPFS from the blockchain, and then the actor accesses the address location to read the file content. The reference architecture attempts to address location restrictions by preserving the sensitive data on IPFS-based network storage that is geographically situated as per regulatory requirements. However, to add an extra layer of protection, individual data elements are encrypted, and the hashes of the files are distributed through the ledger. Large files are distributed through IPFS over the P2P network. IPFS does not dictate any access control by default. The ISA95 enterprise uploads the digital design on the IPFS, and the hash of the file is transmitted to the 3D printing workshop. All interactions and transactions between the stakeholders are stored in the blockchain ledger. Due to storage limitations and size restrictions, larger files are stored in IPFS and their hash is sent to respective participants and stored in the blockchain ledger. Once printing is completed, all IoT devices and camera records will be uploaded to the IPFS and hashed in the blockchain ledger. The hash for the control measures recorded during the printing process is transmitted to the Attestation and Certification Authority accessed via IPFS to verify quality control measures.



* ERP – Enterprise Resource Planning, HMI – Human Machine Interface, PLC – Programmable Logic Controller

Fig. 10. *On-chain and off-chain transaction encryption, adapted from* [70]

In the case of the blockchain-based service architecture for Cloud manufacturing, the authors proposed to relay the dynamic elliptic curve certificate data on a distributed storage system (IPFS) to increase the storage scalability of the proposed architecture [95]. Dynamic certificates and elliptic curve integrated encryption schemes are proposed to enable blockchain-based security services for trust establishment. Diffie–Hellman key exchange is used for the establishment of a symmetric key between IoT–Fog–Cloud channel to encrypt the manufacturing-related message traffic. Non-interactive zero-knowledge proofs are used for verification in the security service to ensure anonymity and unlinkability on dynamic identities stored in the ledger. Additional data used for encryption procedures is offloaded to the extended storage off-chain. The extended storage record is linked to the ledger record with the extended storage key, which is the hash of the multiple data elements. The data consists of the key of storage, certificate, counter data, auxiliary data for private key generation, curve point of zero-knowledge proof, and data set. The experiment showed that the blockchain storage utilization is significantly reduced in the proposed architecture compared to storing all data on the blockchain.

To reduce the load and delay of the network, the blockchain-based platform for IIoT is designed as a light-weighted network architecture (Fig. 11) consisting of an on-chain network and an off-chain network [96]. Under the conditions of the IoT, the computing power of each intelligent device is very limited. Compared with the traditional blockchain mining nodes, the hash computing capability is even less than one-thousandth of the graphics processing unit (GPU) system. The off-chain network handles problems that cannot be solved by blockchain technology, such as storage and complex data processing. The off-chain network has a decentralized off-chain database, namely DHT, which can be accessed by the blockchain. The data is encrypted in the blockchain and stored in the DHT, the access control protocol is written on the blockchain to ensure security, and the off-chain network provides an API interface to read the data in the DHT. The proposed off-chain network further implements a multi-party computation protocol, which allows multiple nodes to perform computing tasks on a common problem in a secure way. In the use case of the proposed concept for manufacturing equipment data sharing, the authors discuss that the shared data is organized into a standardized readable, and writable data format by big data and AI technology on the off-chain network. The shared data is also stored in the off-chain database, while a summary index is generated and stored in the on-chain network. However, the proposed concept is employing general-purpose blockchain solutions and can be implemented on any other blockchain application. The authors do not provide any additional insights into what manufacturing-specific data is written on or off-chain.

In the case of the architecture for secure management of manufacturing data, the off-chain data is stored on the cloud storage system [97]. For the high volume of shared data, the authors present a hybrid approach where a token and conditions on when the token can be used are written on the blockchain, and when the conditions are met the token grants access to particular data on cloud storage. The data itself can go on low-cost cloud-based Write Once, Read Many (WORM) storage owned by the manufacturer, while a token corresponding to the data can be included on the blockchain. The token leaks minimal information about the manufacturing process, allaying potential confidentiality concerns. Upon conditions that can also be spelled out in the blockchain, certain parties have the contractual right to present the token to the manufacturer and be given access to the data.

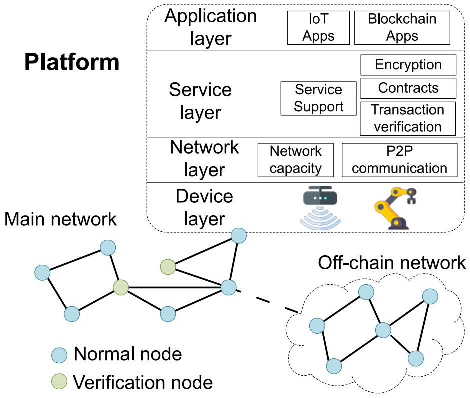


Fig. 11. *Light-weighted blockchain-based network architecture for IIoT, adapted from* [96]

The WORM layer includes a blockchain element because even if data has been placed on WORM storage, there is no guarantee that anyone can find it. The WORM-blockchain combination overcomes this problem by placing the relevant lookup information on the blockchain. The authors, however, do not discuss in detail what kind of manufacturing data is stored off-chain and do not elaborate on how tokens would be implemented (using cryptography or any other tools).

Another concept of blockchain architecture for Cloud manufacturing proposes that a large volume of manufacturing data is stored in decentralized and immutable bid data storage platform like the BigchainDB [98]. Compared to IPFS and cloud platforms proposed decentralized storage is including some parts of blockchain technology such as the consensus mechanism, however it omits safety measures like full replication of the database in each node to provide better scalability. Communication between layers L1 and L2 is established by a new addition to the client middleware as the BigchainDB interface layer. This layer is primarily a middleware software module that resides within the client middleware software architecture and houses event subscribers that subscribe to specific transaction events. These transaction events are emitted by the oracles designed as a part of the smart contracts. Once the manufacturing service is executed an ERC-721 token is created on the L1 network. The oracles on the issuance of these tokens in turn emit their own events which trigger subscribers in the BigchainDB layer to complete the collection of data. The BigchainDB layer collects a large volume of metadata on manufacturing services. The data includes a cryptographically hashed signature of the design file of the final part, detailed dimensional metadata of the part, and necessary information about both the client and the CMaaS platform in terms of their Ethereum identities i.e., wallet addresses. Most of this information quite naturally would involve data of different types and precision. Due to the restrictive nature of the Ethereum ecosystem, there is no default support for many complex data types like variable length strings which have to be used to record modalities like product name or description. BigchainDB as an off-chain solution provides better scalability and enables the storage of complex data types.

3.4 Comparison of the Literature

It is noticeable from the presented literature that a few more concepts propose L1 solutions than L2 and some authors propose a combination of both types of solutions (Fig. 12a). In the case of L1 solutions, the concepts in the literature are mainly proposing the use of scalability solutions that change the consensus mechanism and solutions that change the blockchain structure. For the consensus scalability solution, this is mainly because using alternative consensus mechanisms (e.g. PBFT) can implement a more scalable network, which usually has the properties of a consortium or permissioned network and that corresponds to closed types of SMS organization. The authors thus justify the change of properties in trilemma by saying that the manufacturing world is more closed than the financial one, and there are already proven implementations of these mechanisms, such as Hyperledger. The blockchain structure solutions are mainly presented in concepts that use the specifically designed blockchain network IOTA, which targets the integration of IoT devices into the blockchain network, and there are many of them in the case of SMS.

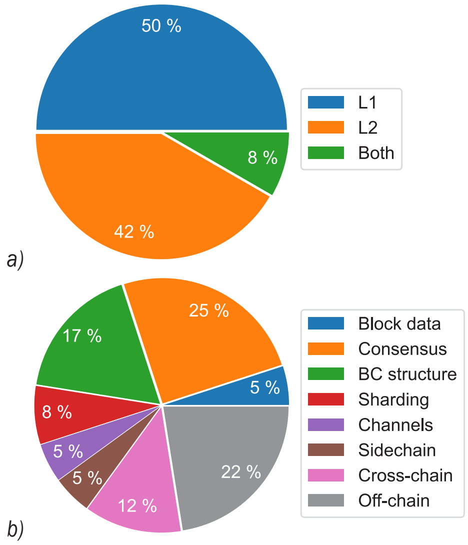


Fig. 12. *a) Proportions of proposed L1 and L2 solutions in literature; and b) proportions of specific scalability solutions proposed in the literature*

In the case of L2 solutions, a group of concepts stands out that suggests the use of off-chain solutions. As already described, most of these concepts want to transfer the data records generated by the manufacturing system from the blockchain to parallel storage infrastructure and consequently relieve the blockchain network. Given the amount of data generated by SMS, it seems reasonable that not all data is stored on such an "energy-intensive" network, but it should be noted that more scalable alternatives also mean less security of stored data. The reason for the highest number of concepts implementing off-chain solutions is that cryptography enables a simple connection between data written off-chain and on the blockchain (hash mappings) and that there already exist several data storage systems that can provide this kind of support (e.g. IPFS). Then, according to the number of solutions, the use of cross-chain solutions follows. Concepts employing cross-chain solutions are similar to the concepts that suggest the use of sidechain technology. The reason for a bigger number of concepts proposing cross-chain solutions instead of sidechain solutions is because cross-chain enables better modularity of the blockchain networks and additional opportunities to build blockchain infrastructure (e.g. existing blockchain networks can connect or disconnect from each other). The main difference regarding user experience is where the identity of an individual system user is created. With sidechain solutions, this happens on the mainchain, and then with that identity, users access other sidechains. With cross-chain solutions, users can join the system on any chain.

In the selected literature, we observed whether the proposed concept is specific to any of the Smart Manufacturing paradigms. Different concepts of organizing manufacturing systems provide for a different number of interactions between entities in the system, which means that blockchain network scalability can be much more important for some concepts than for others. Fig. 13 shows how SMSs are defined in the reviewed literature. In most cases, the authors do not envisage a specific concept of organizing SMS. Only about a quarter of the posts deal with specific examples of SMS, these relate to CloudMfg, Smart Manufacturing supply chain, and other SMS (e.g. SharedMfg). Fig. 13 also shows a comparison between the choice of L1 or L2 solutions in the case of general SMS and specific SMS. In the case of any SMS system, the authors opt for L1 solutions, while for specific SMS the decision for L2 solutions prevails.

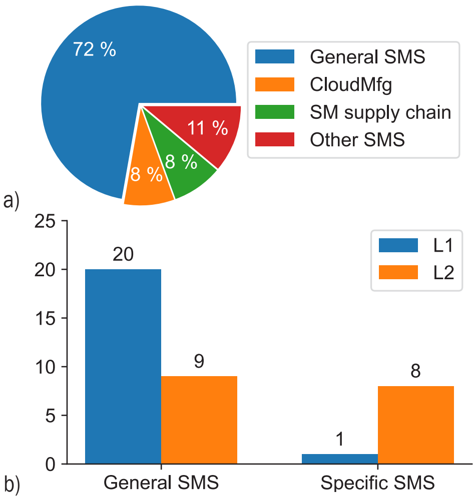


Fig. 13. *a) Proportions of different SMS types implementing scalability solutions in literature; and b) comparison between general and specific SMS concepts regarding the L1 and L2 solutions in the literature*

4 FUTURE DIRECTIONS AND OPEN ISSUES

The presented literature proposes different concepts and solutions however the authors acknowledge that studies have limitations and that there exists a research gap for future work. Based on the reviewed literature the following open research questions (RQ) are highlighted:

- **RQ1**: Do proposed solutions meet the performance requirements of the manufacturing systems?
- **RQ2**: What are the barriers to the real-world implementation and adoption of proposed solutions in a global manufacturing system?
- **RQ3**: How do scalability limitations of blockchain technology affect the performance of a manufacturing system?
- **RQ4**: How increased scalability of the system affect decentralization and security and how reduced trust affects the manufacturing systems?

RQ1 explanation: According to the reviewed literature on blockchain-supported manufacturing regarding the scalability of blockchain technology, most of the authors assume that the scalability of blockchain technology will be a problem when connecting to large manufacturing systems. All of the proposed solutions increase scalability of the blockchain-supported manufacturing, however, a few of the authors are trying to evaluate if such performance results are sufficient for the requirements of global manufacturing systems. The scalability and compatibility of the proposed platform should be further verified and evaluated in a real business environment with more nodes **[70]**. However, it is difficult to assess the number of nodes that are participating in the global manufacturing system. Furthermore, the capabilities of IIoT devices in manufacturing systems are improving. Evaluation of the concepts in the future should include additional devices with specialized hardware designed for blockchain-supported systems **[82]**. In the case of optimization of the consensus mechanism selection concept **[75]**, the author proposes that in the future new consensus mechanism should be developed and that it should be adapted for different properties of manufacturing systems. Consequently, coordination with manufacturing companies is proposed to obtain more realistic performance requirements. Another challenge in answering this question is a representative assessment of different manufacturing systems' performance requirements. The diversity of existing systems seems to present a plethora of requirements. However, studies that would address this question could potentially define the necessary levels of blockchain scalability in relation to the type of manufacturing system. A benchmark would be beneficial for the comparison of different scalability solutions and manufacturing systems.

RQ2 explanation: Given the amount of published literature on blockchain-supported manufacturing, it is surprising that in reality none of the concepts has yet been implemented. Such a platform would make it possible to examine the real-world requirements of the global manufacturing system for scalability, decentralization, and security of blockchain technology [101]. In the case of the concept of blockchain-supported manufacturing industry supply chain management, the authors suggest that they would implement in the future a complete blockchain cross-chain platform based on the high-level model provided by this paper [90]. However, the authors acknowledge some of the barriers to the acceptance of such implementations by the existing manufacturing companies. As it is noted in the industrial implementation challenges, a coordinated effort of engagement must be initiated with manufacturing stakeholders across the industry – designers, job shop service providers, machine builders, regulators, certifiers, public policy, and corporate law [68]. In the future, a thorough study on the barriers to the adoption of proposed solutions in manufacturing would highlight the reasons why blockchain-supported manufacturing is not yet a viable concept in existing manufacturing systems.

RQ3 explanation: Currently, no existing research addresses how scalability limitations affect the performance of a manufacturing system. In the past, blockchain networks that have already implemented scalability solutions have encountered the same limitations. Questions arise as to what would happen if the blockchain network could not process all the transactions for manufacturing services and this would lead to congestion in manufacturing systems [30]. How would manufacturing systems react to this, or would parallel financial channels be established? In addition, there is an increase in the transaction fee in the congestion of the blockchain network, which could affect the price of the manufacturing service. Could transaction fees be higher than the price for manufacturing services? Blockchain represents the financial level that is appended to the manufacturing system in blockchain-supported manufacturing. Given that infrastructure needs to be maintained to operate, in addition to the usual manufacturing roles, financial roles will also emerge. How to ensure that the blockchain-supported manufacturing system emphasizes the role of the manufacturer and not other roles, such as the role of maintaining financial infrastructure. Research on this question would reveal what limitations in manufacturing emerges due to the scalability limitations of blockchain technology.

RQ4 explanation: Most of the concepts discussed in the literature largely neglect the role of the Scalability trilemma, which defines the properties of a blockchain network. Scalability solutions are understood as solutions that increase scalability while maintaining decentralization and security. However, these solutions only increase the scalability of the system at the expense of decentralization and security (they move the properties of the network to another point in the trilemma). The open question thus remains with all the proposed concepts of how increased scalability of the system affects decentralization and security [67]. Does this scalable solution change decentralization and security in such a way that such an approach would no longer guarantee trust in the system [76]? In the literature at the moment, no work has yet addressed how the Scalability trilemma of blockchain technology is reflected in the behavior of the users. Some of the presented solutions allow dynamic movement of the system along the trilemma following the requirements of users and this decision is in their hands. When and why users of the proposed systems will decide to move to the blockchain network with a different position in the trilemma? Which requirements of manufacturing systems dictate the different characteristics of blockchain technology and whether this technology can fulfill them? The analysis of human behavior could potentially answer the question, however, to provide statistically significant results a lot of participants and iterations of the experiment are necessary. Such studies would highlight the requirements of manufacturing systems regarding the trilemma properties of blockchain technology.

5 CONCLUSIONS

The key properties of blockchain technology, which highlight the security and trust issues in decentralized environments, have brought great attention to emerging smart manufacturing concepts. Blockchain technology enables the connection of manufacturing entities that otherwise compete with each other on a global scale in a trustful way. However, this technology also has limitations, namely, the main limitation is a trade-off between scalability, decentralization, and security of the network. Scalability solutions of blockchain technology aim to solve the scalability problem or to at least provide a variety of possible settings of the three main properties in the trade-off.

So far, 36 publications have been published on the topic of scalability solutions in blockchain-supported manufacturing. Different scalability solutions have been used for different specific cases of smart manufacturing systems. L1 and L2 scalability solutions are employed evenly, with L1 solutions being more commonly used for general SMS, while L2 solutions are more commonly used in specific SMS concepts such as Cloud manufacturing. The extent of addressing scalability problems in literature and the number of proposed concepts that are extending general-purpose solutions with manufacturing-specific functionalities increases over time. However, there are still open issues on this topic, especially the lack of analysis of the impact of scalability limitations on the operation of blockchain-supported manufacturing systems. In addition, most of the literature ignores the scalability trilemma, which, despite the proposed scalability solutions, remains a constraint that large blockchain-supported manufacturing systems will encounter sooner or later. Furthermore, there is currently no implementation of the proposed concepts in the industry, which would confirm the need to comply with the limitations of the scalability of blockchain technology in manufacturing systems.

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