Computers & Industrial Engineering 175 (2023) 108827

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

# A blockchain-based interactive approach between digital twin-based manufacturing systems

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ARTICLE INFO

*Keywords:*
Manufacturing system
Digital twin
Collaboration
Blockchain

ABSTRACT

Cloud manufacturing provides an interactive environment for collaboration between digital twin-based manufacturing systems. However, access to the enterprise cloud by a significant number of digital twin systems would lead to bandwidth competition and severe delays. Therefore, the data exchange process needs to be improved in a more reliable and effective way. To tackle this issue, a blockchain-based data interactive approach is proposed to form the peer-to-peer data exchange mechanism between digital twin-based manufacturing systems. First, the manufacturing edge pool is developed given specific manufacturing tasks. The blockchain enables the digital twin manufacturing systems to exchange data effectively and safely. Besides, the application of the blockchain reduces the dependencies of the digital twin systems on the enterprise cloud and improves the flexibility of the workshops. Finally, the effectiveness of this method is verified by a case study on the engine.

## 1. Introduction

With the help of technological evolution and innovation, the rapid growth and globalization of Internet manufacturing services have created very demanding customers who need unique, high-quality, low-cost products that meet their personal needs and preferences (Mourtzis, 2022). Affected by the above, the mass customization (MC) paradigm has become a research hotspot in the manufacturing industry, and MC workshops are emerging in the manufacturing industry. MC combines the advantages of customized and mass production to meet customers' diversified and personalized needs with low cost and fast delivery. It aims to deliver products and services that best meet individual manufacturing needs with near-mass production efficiency (Tseng et al. 2017).

In the MC paradigm, it is essential to provide personalized products or services for consumers through the flexibility and adaptability of manufacturing systems. Due to the significant difference in consumers' individual needs and the small amount of demand in a single time, it is necessary to adapt to the production needs of multiple varieties and small batches in all aspects of manufacturing. Therefore, due to the high requirements for the adaptability and flexibility of manufacturing systems, the large-scale customization paradigm brings the following challenges.

1. **Organizational form**: In particular, manufacturing processes in the high-end customized production industry are complex and multiple, so the product needs to be processed in different working stations. The complexity and coupling of processes bring challenges to the organizational form of manufacturing systems. Considering the complexity and coupling of the manufacturing process, it is very challenging for a centralized manufacturing system to respond quickly to manufacturing requirements
2. **Production mode**: Due to the multi-variety and small-batch production mode, the MC production cannot form a fixed mode. The production adaptability will seriously affect the economic benefits of enterprises. Therefore, on the premise of ensuring product quality, developing an effective collaborative manner to provide the flexibility of the workshop has become a fundamental problem in the customized production workshop.

In the MC paradigm, reconfigurable manufacturing is considered the primary way to achieve flexible production (Mourtzis, 2016), explored by many scholars (Ma, Du, & Jiao, 2020). The modern decentralized

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https://doi.org/10.1016/j.cie.2022.108827
Received 25 April 2021; Received in revised form 10 November 2022; Accepted 16 November 2022
Available online 21 November 2022

**Nomenclature**

| | |
|---|---|
| *MC* | mass customization |
| *DTMS* | The digital twin-based manufacturing system |
| *M2M* | Machine-to-machine |
| *P2P* | peer-to-peer |
| *WIP* | Work in progress |
| *EP* | The edge pool |
| *Ep_m* | the manufacturing edge pool |
| *Ep_set* | the edge pool set |
| *T* | the manufacturing task |
| *Mg* | the manufacturing combination required in the process |
| *Ep_f* | the fixed edge pool set |
| *MKT* | Merkle tree |
| *POW* | Proof of work |
| *POM* | Proof of manufacturing |
| $Pom_i^t$ | The proof of manufacturing capacity of consensus node *i* in *t* consensus cycles |
| $M_i$ | The alternative work proof provided by consensus node *i* for the consensus cycle |
| *ep* | the edge pool |
| *Bc* | the blockchain |
| $Bc\_set_{node}$ | the collection of blockchains in node |
| *D* | the data required by the node |
| $Node_h$ | the node that requests the data |
| $ep^h$ | the primary edge pool where $Node_h$ is in |
| $Node_P$ | the node that owns the data |
| $Node_{set}$ | all nodes that own the data |
| *R* | the data demand |
| F(set) | the node with the smallest network occupancy in the query set |
| Transfer(a,b,data) | the transfer *data* from location node *a* to node *b* |

production mode has appeared and partially replaced the traditional centralized production network to improve the adaptability of the manufacturing system (Mourtzis & Doukas, 2012). It can generate the manufacturing route adaptively according to the production situation of the workshop. A large number of meaningful data drives the operations of the manufacturing systems to achieve accurate inspection of manufacturing status and make better decisions (Mourtzis, 2020).

Besides, the digital twin-based manufacturing system (DTMS) has the characteristics of real-time, high integration, and traceability (Leng et al., 2021). The data interaction between the physical space and virtual space of the digital twin system can observe, analyze and control the manufacturing process in real time (Liu, Bao, et al., 2020). Therefore, digital twin technology is an effective method to realize the precise control of the manufacturing process, which has been gradually applied in the manufacturing industry (Liu, Lu, Zheng, Shen & Bao, 2022; Liu, Sun, Zheng, Lu & Bao, 2022). However, the advantages mentioned above depend heavily on the integrity and security of data (Suhail et al., 2022).

Networked collaborative manufacturing provides a solution for data interaction between manufacturing systems (Barenji, Guo, Wang, Li, & Rong, 2021). Under the influence of the networked collaborative manufacturing concept, most enterprises adopt the enterprise cloud system to provide data transmission on networked collaborative manufacturing. However, the dynamic data demand of digital twin systems is more frequent, putting forward higher requirements for data transmission (Wang, Wang, Yang, & Wang, 2019). If all the manufacturing systems are connected to the enterprise cloud, bandwidth competition and severe delay will be problems in the cloud manufacturing mode. Besides, the cost of virtual packaging of cloud manufacturing resources and the severe hysteresis of the network cannot be ignored.

Furthermore, once the cloud fails, the services based on cloud manufacturing will collapse, significantly reducing the flexibility of workshop manufacturing. To solve the above problems, this paper explores a peer-to-peer (P2P) collaboration method between DTMSs and constructs an interactive framework of cloud-edge collaboration. The self-organizing generation edge pool mechanism is explored, and the transmission mechanism based on blockchain is built on the edge pool. The blockchain-based data transmission method is studied to realize the information interaction between systems to remove the cloud system's dependence. The above collaboration method can meet the data demand of high-performance manufacturing systems to ensure production flexibility and manufacturing capacity.

The remainder of this paper is organized as follows. Section 2 summarizes the research on the digital twin, cloud manufacturing and collaborative manufacturing. In Section 3, the framework of the collaboration method between DTMSs in the cloud-edge interplay workshop is proposed. Section 4 introduced the generation method of manufacturing edge pool. In Section 5, the data interaction method between DTMSs based on blockchain is proposed. Section 6 verifies the proposed method by a case application, and Section 7 concludes the paper.

## 2. Literature review

With the development of technologies such as artificial intelligence, big data, and cyber-physical system, digital twins and cloud manufacturing have been highly concerned in the academic field (Wang, Xu, Zhang, Bao, & Zhong, 2019, Wang et al., 2019). This section reviews the research progress of digital twins, cloud manufacturing workshops, and the method of data transmission. Finally, the research gaps are summarized and highlighted.

### 2.1. Digital twin-related research

Since the concept of digital twins was proposed by Grieves (2014), relevant scholars have researched it. From 2003 to 2016, due to the limitations of computer technology and artificial intelligence technology, the research progress of digital twins is relatively slow. Since 2017, many explorations and reviews kinds of literature have emerged. Some scholars summarized the concept, the reference model, and the development direction of digital twins (Tao, Zhang, Liu, & Nee, 2019; Lim, Zheng, & Chen, 2019; Lu, Liu, Kevin, Wang, Huang, & Xu, 2020). Tao and Qi (2019a) pointed out that digital twins have great potential to bring massive value to manufacturing. Other scholars in the field also explored the critical technology and application of digital twins.

Tao, Cheng, et al. (2018) first proposed the concept of a digital twin workshop and explored the application prospect of the digital twin applied to product design, manufacturing, and service. In the research of workshop level, Leng, Liu, et al. (2020a) proposed the concept of an open-architecture machine tool and developed it as a new class of machine tools comprising a fixed standard platform. Zhou, Zhang, Li, Ding, and Wang (2020) proposed the data-driven digital twin manufacturing cell, which can support independent manufacturing through intelligent perception, simulation, understanding, prediction, optimization, and control strategies. In the research of the assembling level, Zhuang, Liu, and Xiong (2018) proposed a digital twin management control framework and applied it in the assembly field. Sun, Bao, et al. (2020) proposed a method based on digital twins for assembly, adjustment, and coupling to assemble high-precision products efficiently. In the research of the machining level, Liu, Bao, et al. (2020) proposed a machining-oriented digital twin modeling method based on biomimicry, emphasizing that the digital twin model changes with the machining process. Tong, Liu, Pi, and Xiao (2020) proposed a real-time data application and service based on intelligent machine tool digital twins. This method is used for data visualization and analysis in digital twins, including the machining trajectory, the machining status, and the energy consumption. Kong, Hu, Zhou, and Ye (2020) proposed a method of data construction that can provide data adaptively according to the requirements.

### 2.2. Cloud-edge interplay workshop

Cloud manufacturing provides the possibility of efficient collaboration among manufacturing systems, and relevant scholars have explored this issue. Lu, Xu, and Xu (2014) studied the operation mechanism of the cloud manufacturing system in several different business scenarios. Most cloud manufacturing systems have three deployment modes: private, community, and public. After that, Lu and Xu (2019) added a typical system architecture for cloud manufacturing equipment based on cyber-physical production systems. It allows manufacturing equipment to be connected to the cloud and provides on-demand manufacturing services. Liu, Jiang, and Jiang (2020) proposed a system framework based on the environment of cloud manufacturing. It guides the rapid system configuration and easy operation of cyber-physical production systems.

In the research on cloud-edge collaboration, Ding, Chen et al. (2019) proposed an intelligent factory architecture based on cloud-edge collaboration and the configuration method of edge nodes and cloud services. It can realize real-time production status monitoring and autonomous production process response control of intelligent factories. Wang, Wang, Yang, and Wang (2019) proposed a data processing architecture combining edge computing and feedback control, which can meet real-time monitoring functions, historical data traceability, and flexible call. Man, Zhao, Peng, and Li (2020) proposed a scheduling method for large-scale factory access based on cloud-edge collaborative architecture to improve the utilization of computing resources.

### 2.3. Data transmission method in the manufacturing field

In the cloud-edge collaborative manufacturing environment, it is possible for rapid collaboration between manufacturing systems. Communication is the premise of cooperation among manufacturing systems.

To realize direct communication between manufacturing systems, Meng, Wu, Muvianto, and Gray (2017) proposed the machine-to-machine (M2M) message-passing mechanism based on ZeroMQ, which meets the requirements of communication flexibility, efficiency, and cross-platform compatibility. Lu and Asghar (2020) proposed general architecture to realize P2P semantic communication between industrial machines supporting technologies of cyber-physical systems. Altun, Tavli, and Yanikomeroglu (2019) use the blockchain-based method to model the information interaction of furniture to ensure communication security. Gehrmann and Gunnarsson (2020) built a security architecture to allow data sharing and ensure the security of industrial control systems. However, in the dynamic workshop, the above methods cannot solve large-scale data transmission between digital twin systems.

Since the blockchain is proposed by Satoshi Nakamoto, it has received extensive attention. In recent years, in the field of manufacturing, blockchain has gradually gained application. Lohmer and Lasch (2020) explore the potential and the existing barriers of blockchain technology in operations management and manufacturing through empirical study. As one of the promising innovative technologies, blockchain enables transparent, secure, and timely data exchange via smart contracts. Jiang, Ge, Yang, Wang, and Li (2020) applied blockchain in the transmission of the Internet of things system to improve the efficiency of data exchange. Yin, Bao, Zhang, and Huang (2017) proposed a blockchain-based approach for communication security in cyber-physical systems. Leng, Yan et al. (2019) proposed a novel iterative bi-level hybrid intelligence model named ManuChain to eliminate inconsistency between holistic planning in individualized manufacturing systems. Besides, Leng, Ruan et al. (2020b) discussed using blockchain to realize sustainable manufacturing. Huang, Wang, Yan, and Fang (2020) apply blockchain to digital twin technology to realize product lifecycle data management. Kouhizadeh, Saberi, and Sarkis (2021) considered blockchain technology sets the stage for theoretical observations for implementation in sustainable supply chains. In the MC paradigm, Yetis et al. (2022) connect customers with factories through blockchain to form a trusted data set to provide optimized management. Suhail et al. (2022) build some trusted digital twins to provide an aggregated view of the complex physical system through blockchain-based data storage. However, under the MC paradigm, there are still research gaps in data exchange methods to improve collaboration between DTMSs.

### 2.4. Research gaps

Based on the above literature review, some things could be identified as follows:

(1) Digital twin technology has been widely studied by experts, scholars, and enterprises, especially in manufacturing, with a comprehensive application value and application prospect. Their research shows that the virtual decision-making process in the digital twin system relies heavily on twin data. The twin data include product model data, manufacturing process data, etc. However, there is a lack of research on the data transmission mechanism between DTMSs;

(2) The manufacturing mode under cloud-edge collaboration has been gradually recognized by scholars in related fields. They have relevant explorations in system architecture, production monitoring, scheduling, etc., which have a lot of potential and application value to improve the production efficiency of the production line. However, the research of cloud-edge collaborative workshops mainly focuses on resource allocation and process reconfiguration under the workshop rather than data transmission.

(3) There have been related studies on the communication mechanism between machines in the environment of cloud manufacturing, but these methods cannot achieve large-scale data transmission. Besides, blockchain as a method of information interaction has been initially explored in industrial applications, and it has great potential to help manufacturing systems collaboration.

Therefore, based on the above conclusions, a collaborative approach between DTMSs is urgently needed to meet the data requirements in the manufacturing life cycle. Based on the collaboration between DTMSs during the product manufacturing whole life cycle needs to be an in-depth study of the above aspects, which is the focus of this study.

## 3. The definition and data requirements of DTMSs

This section proposes the concept of the DTMS and analyzes its data requirements. Then, a cloud-edge collaborative framework is proposed to connect the DTMSs.

### 3.1. The definition of the DTMS

The DTMS is an intelligent system with perception, prediction, decision-making, and control. It perceives the manufacturing environment, analyzes and predicts potential manufacturing problems, makes decisions on the issues encountered using internal or external data, and controls the machine according to its own decision. Besides, it can update the database through continuous data. So, the DTMS has a more robust manufacturing capacity than the traditional manufacturing system. Therefore, we define the DTMS as follows:

**Definition 1**. the DTMS is a kind of manufacturing system that integrates the characteristics of the digital twin. As shown in Fig. 1, the DTMS has four-dimensional limited intelligent manufacturing space, including physical, digital, data, and decision space. The integration of these four spaces enables DTMS to have strong cognitive and learning abilities, such as self-decision-making, self-execution, and self-improvement. It maximizes quality and throughput while maintaining flexibility and reducing costs.

The framework comprises four essential spaces: physical space, digital space, data space, and decision space. Their functions are as follows.

(1) Physical space: the container of physical manufacturing resources, such as work in progress (WIP), and intelligent manufacturing equipment;

(2) Digital space: the container of virtual manufacturing resources, such as virtual WIP, virtual manufacturing equipment and virtual manufacturing process;

(3) Data space: integrated and dynamic database, including manufacturing monitoring data;

(4) Decision space: the ability of intelligent decisions based on data.

### *3.2. The data requirements of the DTMS during the manufacturing process*

The DTMS is a highly controlled system with a solid manufacturing capacity. It can perceive and simulate the production process based on real-time data and use historical data to understand, predict and optimize manufacturing performance. When the product flows into the DTMS, the DTMS needs to build its high-fidelity digital twin model and control its manufacturing quality precisely based on the manufacturing data. Different from other manufacturing systems, DTMS requires different amounts of data. The data needed by DTMSs are analyzed from two aspects of the MC paradigm.

1. Manufacturing process: products are usually composed of multiple parts and components with their key and different manufacturing processes (Qin, et al. 2022). These manufacturing processes are diverse, including at least two different machining and assembly processes (Qin, Tao, & Liu, 2018). As shown in Fig. 2, the manufacturing sequence represents the physical manufacturing process, and its mapping in virtual space is called the manufacturing process mapping network. The node of the process network in the virtual space is a digital twin model that describes the physical state with high fidelity. This high-fidelity description requires more and more complete data than traditional methods.
2. Operation process: the DTMS needs to receive the manufacturing task and understand it during the operation process. After understanding the task, it is necessary to obtain the accurate product digital twin model to make the manufacturing decision. However, products are usually completed by different manufacturing systems according to manufacturing processes, so frequent information interaction is required between manufacturing systems. As shown in Fig. 2, the virtual space's flow direction arrow is a single product's main data flow direction. The nodes organized by these flow arrows are manufacturing systems that need to complete data exchange.

Most of the above procedures are based on data analysis, so the DTMS is a data-driven system that relies on manufacturing process data. The basis of the collaboration between DTMSs is that the manufacturing system can exchange data adaptively according to the manufacturing process on demand. The data demand of DTMS that may be involved in the above process has been summarized in Table 1.

It can be seen from the above that the operation process based on the digital twin system mainly needs task data, digital twin model, object data, and historical data. A universal collaboration scheme is urgently needed for analyzing tasks adaptively and improving decision accuracy, which can exchange massive data between DTMSs. To achieve connectivity, achieve the purpose of enhancing the collaboration between DTMSs.

## 4. The generation method of the manufacturing edge pool

In order to realize the cooperation between digital twin systems, it is necessary to connect them effectively. In this section, based on the tasks of each manufacturing system, we will build a manufacturing edge pool to promote their cooperation.

### *4.1. The interconnection architecture of DTMSs in cloud-edge interplay workshop*

The interconnection architecture of the cloud-edge interplay workshop is shown in Fig. 3. It can fully use the idle resources of the equipment, save energy and time, and significantly reduce the pressure of data explosion and network traffic. Cloud can make decisions on on-site resource allocation schemes and schedule the production situation of the workshop through specific manufacturing tasks and the status of field equipment. The edge node mainly monitors and analyzes manufacturing data in real time. The cloud-edge interplay workshop can perform virtual debugging and simulation optimization on the physical model combined with real-time perception data. Besides, under the

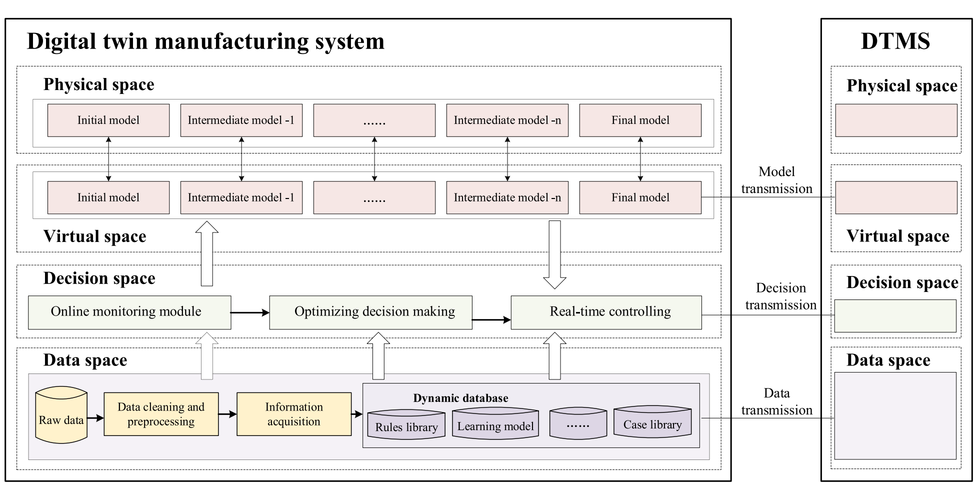


**Fig. 1.** The structure of DTMS.

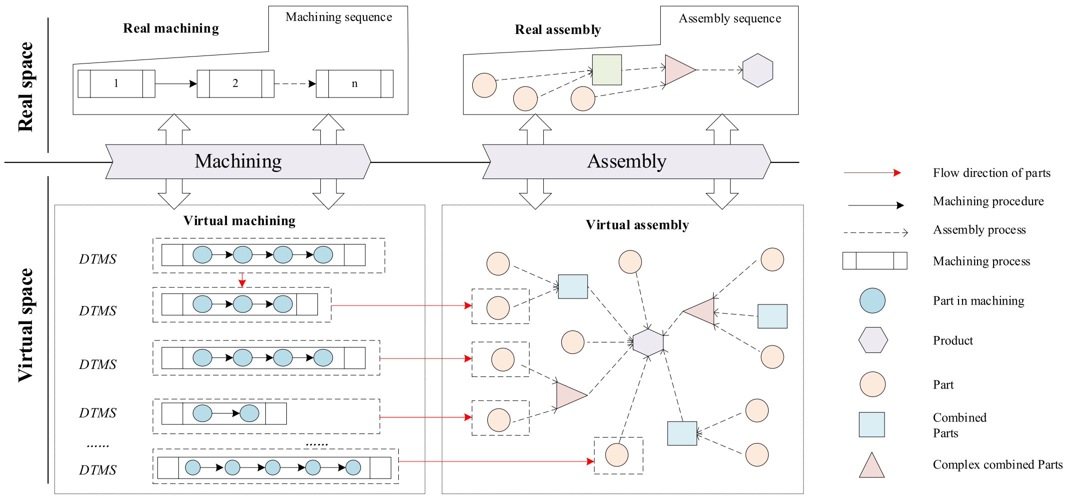


**Fig. 2.** The manufacturing process based on digital twin.

**Table 1**
Data transmission content.

| Data demand | Data type | Data content |
|---|---|---|
| Task information | Manufacturing features | Manufacturing features and sequence of products |
| | Manufacturing requirements | Accuracy requirements of geometric dimensions of products |
| Model information | Model data | Data information on overall modeling |
| | Error data | State data of actual product modeling |
| | Surface state data | Actual performance data of the product |
| Historical data | Manufacturing cases | Similar manufacturing cases |
| | Equipment status data | Similar cases of equipment |
| | Manufacturing decision cases | Manufacturing information decision scheme |
| | Process control cases | The data control scheme in the manufacturing process |
| | Tool status case | Actual case analysis status of the manufacturing process |

sensing control of higher-level nodes, the node groups of the same layer can cooperate to complete the manufacturing tasks efficiently.

The enterprise cloud decision is realized on the enterprise cloud. It perceives the changes in user orders in real time, analyzes the manufacturing tasks through extensive industrial data, and recognizes the optimization of manufacturing service combinations and production scheduling in the enterprise cloud. It adaptively allocates the corresponding tasks by sensing the changes in tasks and requirements.

The edge node corresponds to each manufacturing system in the enterprise. The digital twin model is responsible for sensing and controlling the real-time status of production equipment (i.e., cutting force, temperature, energy consumption, humidity, etc.). It is responsible for the real-time perception and control of the manufacturing process data (i.e., process parameters, working conditions, manufacturing time, efficiency, etc.). The perception records the data in the collaborative production process (i.e., cooperation mechanism, communication protocol, parameter settings, etc.). It records the experimental data of the sensing and control products in the simulation process and the performance parameters (i.e., geometric error, surface roughness, precision, machining parameters, etc.) obtained in the actual process; the different quality information (i.e., precision, roughness, residual stress, etc.) corresponding to different manufacturing environments (i.e., rough machining, temperature, feed rate, clamping mode, etc.) are sensed and recorded.

To sum up, the tasks and requirements of cloud edge nodes are shown in Table 2.

### 4.2. Generation method of manufacturing edge pool

After connecting the manufacturing system based on the above method, when facing different manufacturing tasks, the system will generate different manufacturing routes, and most of these routes will be

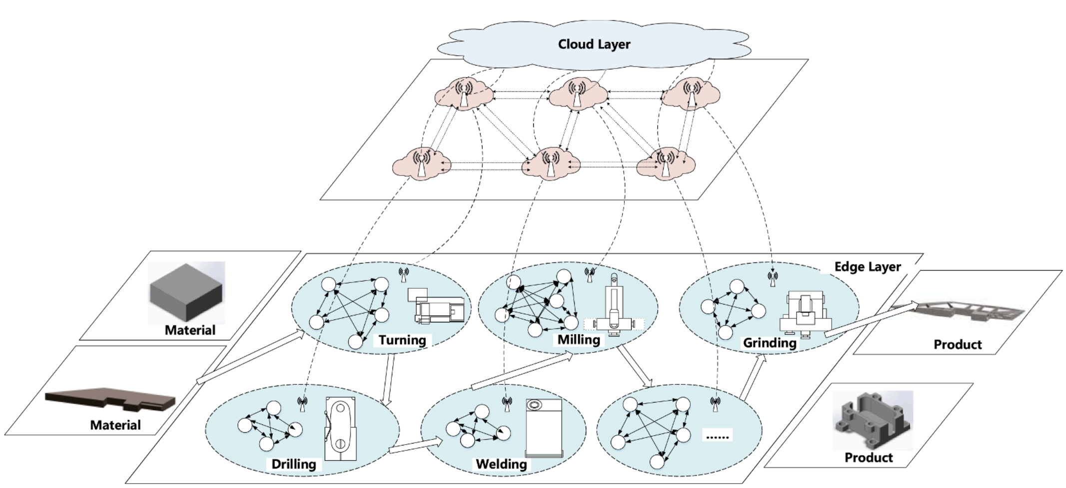


**Fig. 3.** the interconnection architecture of DTMSs in cloud-edge interplay workshop.

**Table 2**
The tasks and requirements of cloud edge nodes.

| Node classification | Management content | Information content |
|---|---|---|
| Cloud layer | Production scheduling | Customer order, task schedule, cloud failure rate, cloud fault information, enterprise manufacturing resources, and capabilities, etc |
| | Production task | Production schedule, WIP rate, failure rate, fault point information, etc |
| Edge layer | Quality control process | Process parameters, working conditions, manufacturing time, efficiency, manufacturing requirements, control methods, etc |
| | Collaborative production | Cooperation member, cooperation mechanism, communication protocol, parameter setting, cooperation logic, etc |
| | Equipment | Equipment ID, cutting force, energy consumption, use frequency, function, manufacturing capacity, failure mode, etc |
| | Manufacturing process | Process parameters, product parameters after each process parameters, clamping mode, etc |
| | Product quality | Manufacturing accuracy, roughness, residual stress, etc |

executed across regions. Fig. 4 shows the manufacturing route of parts from blank to product, which is often processed by multiple manufacturing systems. Therefore, to improve data transmission efficiency and collaboration between manufacturing edge nodes, it is necessary to construct corresponding groups according to manufacturing technology. Consequently, we define the edge pool (EP) as follows:

**Definition 2**. edge pool refers to a group formed by a part of edge nodes, which can help quickly establish peer-to-peer transmission. There are two kinds of edge pools: the fixed edge pool and the manufacturing edge pool. The cloud generates the fixed edge pool, mainly divided according to the type of DTMS. The manufacturing edge pool is developed according to the manufacturing routes. The edge pool can be expressed by Formula 1 as follows.

$$EP = \{DTMS, DTMS, DTMS, ......\} \tag{1}$$

The generation method of the manufacturing edge pool is shown in Fig. 5. The manufacturing edge pool connects many independent nodes in the edge pool. In this way, each node can be connected through the corresponding protocol from the beginning to the end of the manufacturing technology. The specific search methods are as follows:

Step-1. Firstly, the cloud sends the task, assigns the corresponding edge nodes according to the manufacturing process, and transmits the information to the cloud layer.

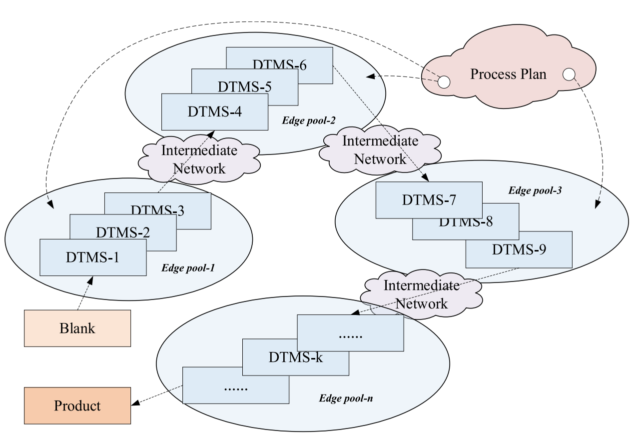


**Fig. 4.** the manufacturing route of parts from blank to product.

Step-2. According to the task type, the cloud layer will give priority to the previously used manufacturing edge pool (reduce the number of blockchain generations).

Step-3. When the cloud layer obtains the task requirement, it sends the control instruction to each node, gives the task number, and proposes the corresponding node protocol;

Step-4. Each node obtains the information of edge nodes that they need to connect and tries to connect by dialing directly through the network;

Step-5. When the connection is successful, a point-to-point connection is formed through the identity handshake to form a manufacturing edge pool.

Algorithm 1 summarizes the process of generating a manufacturing edge pool. In Algorithm 1, $Ep\_m$ represents the manufacturing edge pool, $Ep\_set$ represents the edge pool set, $e$ represents the edge node, $T$ represents the manufacturing task, $Mg$ represents the manufacturing combination required in the process, $Ep\_f$ represents the fixed edge pool set. The pseudo-code for Algorithm 1 is as follows.

Algorithm 1: Generation of manufacturing edge pool in a cloud-edge collaborative workshop

**Input**: $T$
**Output**: $Ep\_m$
/* Select from the historical edge pool */
Analyze the $T$ to get $Mg$
**for** $Ep^i$ **in** $Ep\_set$ **do**
  **if** $Ep^i == Mg$ & $Ep^i == Available$ **do**
    $Ep^i \rightarrow Ep\_m$
    $find = true$
    **end for**
  **end if**
**end for**
/* Generating a new edge pool */
**if** $find!$ **do**
  **for** $Ep^i$ **in** $Ep\_f$ **do**
    **for** $e^j$ **in** $Ep^i$ **do**
    **if** $e^j == edge$ & e==free **do**
      $e^j \rightarrow Ep\_m$
    **end if**
    **end for**
  **end for**
**endif**

## 5. The blockchain-based method of data exchange between DTMSs

Manufacturing enterprises mainly use the license network connection, which requires each node to have the corresponding access certificate to enter the system. This section uses edge nodes for data exchange based on blockchain, ensuring effective collaboration between DTMSs.

### 5.1. Blockchain structure

In the cloud edge interplay workshop, each DTMS is an edge node. Due to the strong security and privacy of manufacturing enterprises, the blockchain used in this paper is the type of permissioned blockchain, which has higher requirements for the credibility of members. An appropriate security mechanism should be adopted at the network level, including identity and transmission security. Identity security is the security requirement of the permissioned chain to ensure peer-to-trust. Generally, digital signature technology is used to sign the whole life cycle of nodes (such as node interaction, voting, synchronization, etc.) so as to realize the admission permission of the license chain.

Blockchain is an encrypted ledger with a chain structure. The encryption method mainly uses the hash algorithm, which realizes the irreversible mapping from plaintext to ciphertext. Blocks are connected by the hash pointer encrypted by the hash algorithm. Because of the strong correlation of the chain data structure, the blockchain has

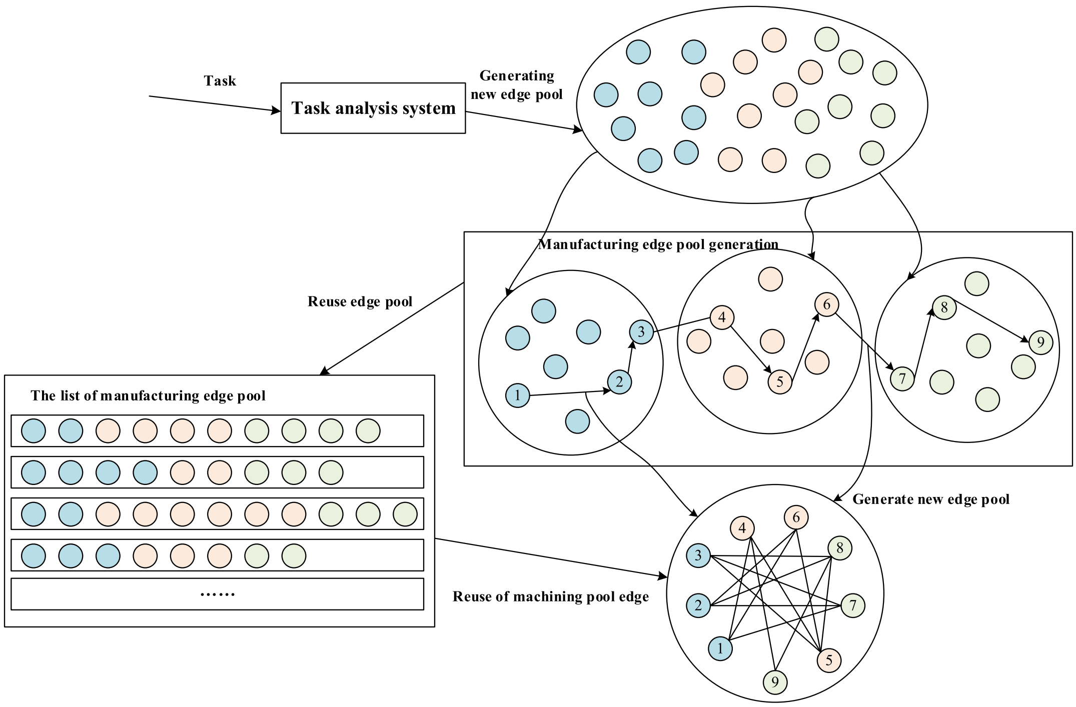


**Fig. 5.** Generation method of manufacturing edge pool.

tamper-proof characteristics. This structure determines the binding relationship between data. When specific data tamper with, the relationship will be destroyed.

The essential unit of the chain structure is "block". The basic content is shown in Fig. 6. The block consists of a header and a body. The block body contains a certain number of transaction sets, and the blockhead maintains its association with the previous block through the previous hash, thus forming a chain structure. Through the root hash generated by the Merkle tree (MKT), the integrity of the transaction set of the block body is verified quickly.

The data storage mode adopted in this paper is the off-chain model. It means that the business data is partially or entirely stored outside the blockchain, and only pointers and other data proving the existence, authenticity, and validity of business data are stored in the blockchain. Due to the decoupling from the blockchain, the model has good privacy and scalability, which is very suitable for manufacturing enterprises with a low degree of decentralization, strong privacy, and large throughput. The blockchain mainly publishes and records the manufacturing task, execution information, and interactive information between the digital twin systems, as shown in Table 3.

### 5.2. Consensus mechanism and block communication mechanism

As shown in Fig. 7, the nodes in the edge pool, namely DTMSs, are connected through the blockchain, and each edge node contains a consensus node, a verification node, and a storage node. Consensus nodes participate in the broadcast and verification of transactions. In block packaging and consensus, the verification node is responsible for the broadcast and verification of blocks. The storage node stores the generated data and receives the data transmitted by other nodes. The blockchain is saved on the consensus node and the verification node. Therefore, each node can maintain an identical blockchain for data transmission and interaction.

There is no central database like the traditional database system in the blockchain network. Since each node is peer-to-peer, the consensus mechanism is needed to ensure that all peer nodes can cooperate effectively. The consensus mechanism is an algorithm for blockchain transactions to reach distributed consensus. Traditional blockchain projects adopt a proof of work (POW) algorithm strongly dependent on massive calculation. On the one hand, using POW in industrial scenarios will waste computing power and energy. On the other hand, verification speed is slow, and it is challenging to implement effective data interaction.

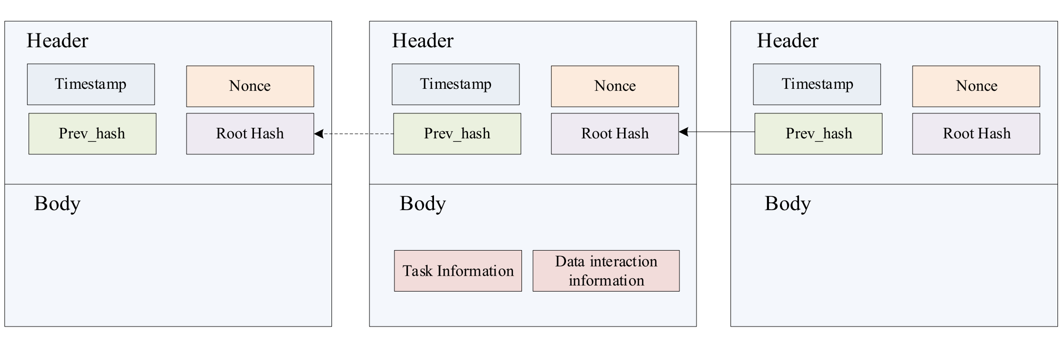


**Fig. 6.** Blockchain structure.

**Table 3**
Data recorded in the blockchain.

| Type | Content | Description | Components | Examples |
|---|---|---|---|---|
| The manufacturing record | Machining requirements | Record the manufacturing time, task details, and part number | (Task time, part name, operation number, planned completion time) | (10:05, PTVA10212, 10, 12:07) |
| | Machining procedure | Machining process | (Feature number, operation name, operation parameter, expected completion time) | (Feature-3, milling, (1045,136), 11:07) |
| | Machining completion | Report the process completion according to the process steps | (process number, completion time) | (Process-m-12,10:28) |
| | Quality inspection information | Key measurement measured values of key machining features | (machining feature number, feature data, feature value) | (Feature-3, hole, (10, 3)) |
| Data interaction between DTMSs | Transmit demand information | Release the required data requirement | (Part number, main features, composition information, data requirements) | (PTVA10212-11, Hole, Machining parameters) |
| | Data provides information | Edge node information that can provide data | (node location, transmission status) | (Node-4, Free-4%) |

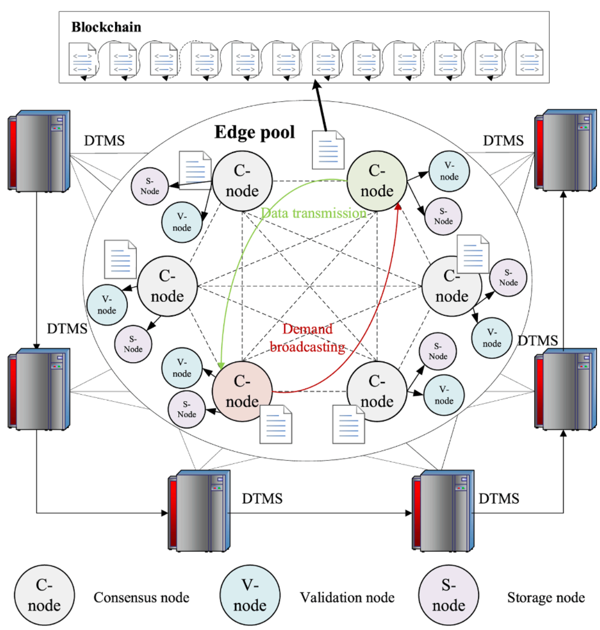


**Fig. 7.** Blockchain-based data exchange between DTMSs.

This paper adopts the proof of manufacturing (POM) consensus mechanism to overcome the above problems. The probability that the consensus node successfully adds blocks to the blockchain is determined by the ratio of manufacturing workload in the consensus period.

$N$ is the number of consensus nodes in the edge pool. $M_i$ is the alternative work proof provided by consensus node $i$ for the network in the consensus cycle. Then, the proof of manufacturing capacity of consensus node $i$ in $t$ consensus cycles is shown in Formula (2).

$$Pom_i^t = \frac{M_i}{\sum_{j=1}^{N} M_j} \tag{2}$$

The consensus algorithm of POM is shown in Formula (3).

$$SHA256(SHA256(header + body), Node_i, nouce\ ) \leq f\left(Pom_i^t\right) \tag{3}$$

In Formula (3),*header* represents the header of the blockchain, *nouce* represents the random number,$f(x)$ is a linear function. The larger the value of $x$, the greater the value of $f(x)$. Therefore, the more parts processed by nodes, the greater the probability of packing blocks.

The more manufacturing tasks the DTMS completes, the greater the probability that the consensus node successfully adds blocks to the blockchain. Compared with the POW consensus mechanism, the POM consensus mechanism makes the consensus process between consensus nodes not need to waste a lot of computing power to complete meaningless hash computing tasks.

After the consensus node generates blocks, the generated blocks must be propagated to all consensus nodes and verification nodes. The verified blocks can be added to the blockchain. The blockchain network used in this paper is generally based on the gossip protocol to achieve flooding propagation. When the consensus node generates a new block, consensus node $i$ needs to transfer the *block* to other consensus nodes for verification. When a new block is generated, its propagation and verification process is as follows:

1) Between consensus nodes: consensus node $i$ transmits the block to other consensus nodes;

2) Between consensus node and verification node: consensus node $i$ transmits *block* to its verification node for verification;

3) When the number of verification nodes passes 2/3 of the total number, the verification passes, and the next block is packaged.

### 5.3. Data request and transmission based on smart contract

In order to reduce the complexity of data sharing and management, this paper proposes a smart contract for industrial data transmission by using blockchain data to query data and promote peer-to-peer data transmission between edge nodes. Each node can query the node information recorded on the blockchain through the smart contract, as shown in Fig. 8, mainly including the data query and the confirmation process of edge nodes based on the blockchain. When the edge node obtains the task, the node analyzes the manufacturing requirements. The nodes with data are queried in the edge pool and sorted according to the network status. The node selects the optimal supply node and establishes the connection.

The smart contract includes four parts: node query, network status query, node sorting, and transmission confirmation. The node query contract is to query the node information of the data in the edge pool. The network query contract returns network status information by inputting node information. The state scheduling contract is to sort the priority of nodes by synthesizing the network load and processing load of nodes. The transmission confirmation contract is to confirm the data and identity information transmitted by both parties.

The specific steps are as follows:

Step-1. Firstly, the smart contract is used to release the query request of the nodes' data they need in the blockchain;

Step-2. The system returns the status data of the current owned node;

Step-3. All nodes with data are sorted according to the current network load status and returned to the DTMS for transmission and release requirements;

Step-4. The DTMS selects the transmission node and issues the data exchange request through the smart contract.

Step-5. The data provider verifies through the smart contract. The two nodes are connected while the verification is successful.

### 5.4. Blockchain-based data change between DTMSs

Both the fixed edge pools and the generated machining edge pools

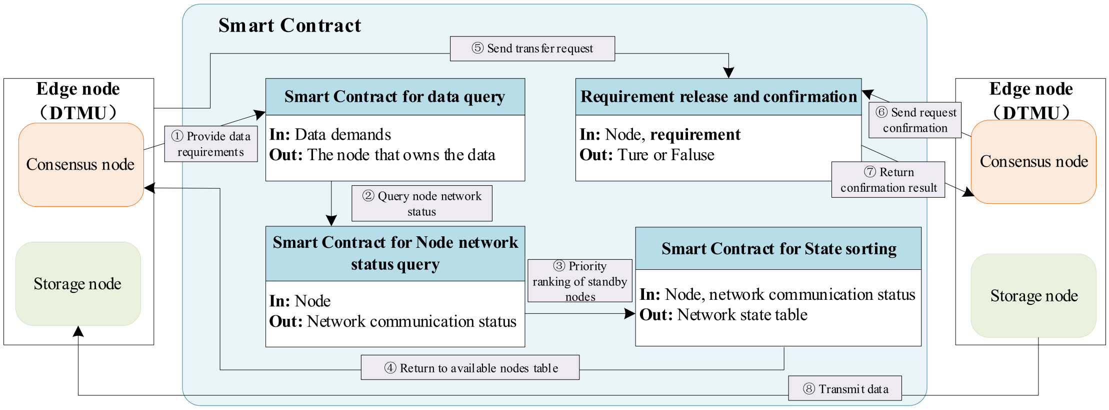


**Fig. 8.** Smart Contract.

have their corresponding blockchain. Therefore, there will be multiple blockchains under a single node. Among them, the main edge pool controlled by the cloud layer has the main blockchain. In the machining edge pool generated is the sub-blockchain. Therefore, the data requester publishes the required data in the currently connected state edge pool. After each edge node obtains the relevant data, it needs to analyze and query its own sub-blockchains, and generate and return report information. The node self-queries its own data, receives the edge node of the current edge pool, and directly establishes the connection to form the peer-to-peer transmission.

The method of establishing the connection between DTMSs is shown in Fig. 9. All independent edge pools are connected through the connection protocol of the manufacturing edge pool. Any node of the edge pool can continuously request and query the information of the nearest node through the principle of the logical distance between the fixed edge pools and the manufacturing edge pools. The data transmission can be carried out point-to-point based on the information transmission between different stages. A brief, direct connection edge pool is used to query the general graph in each part of the point. The specific principles are as follows:

1. The node first searches for the node through the main blockchain in the edge pools where it belongs to;

2. If it is not found in the edge pool where it belongs, the node will request to query the node existing in the sub-blockchains.

3. If the owned node is not found in the sub-blockchains, request other nodes in the edge pool to query its main blockchain to find nodes.

4. Repeat the above method to search across edge pools.

Algorithm 2 summarizes the data query proces and transmission across edge pools. In Algorithm 2, *ep* represents the edge pool, *Bc* represents the blockchain, $Bc\_set_{node}$ represents the collection of blockchains in node,*D* represents the data required by the node, $Node_h$ represents the node that requests the data, $ep^h$ represents the primary edge pool where $Node_h$ is in, $Node_P$ represents the node that owns the data, $Node_{set}$ represents all nodes that own the data,R represents the data demand, F(set) represents the node with the smallest network occupancy in the query set, Transfer(a,b,data) represents the transfer *data* from location node *a* to node *b*. The pseudo-code for Algorithm 2 is as follows:

Algorithm 2: Blockchain-based data transmission between DTMSs

**Input**: $Node_h; R$
**Output**:$Node_p; D$
/* Find the node that owns the data */
Get the $Bc\_set_{node}$ of the $Node_h$;
–
**for** *Bc* **in** $Bc\_set_{node}$ **do**
$Node_h$ send the *R* in *Bc*;
**if** node get the R **do**
Each *Node* send the *R* on the *Bc* of their *ep*/* Send demand instructions across edge pools */
Find the $Node_P$ by the *Bc*;
$Node_P \rightarrow Node_{set}$;
**end if**

(continued on next page)

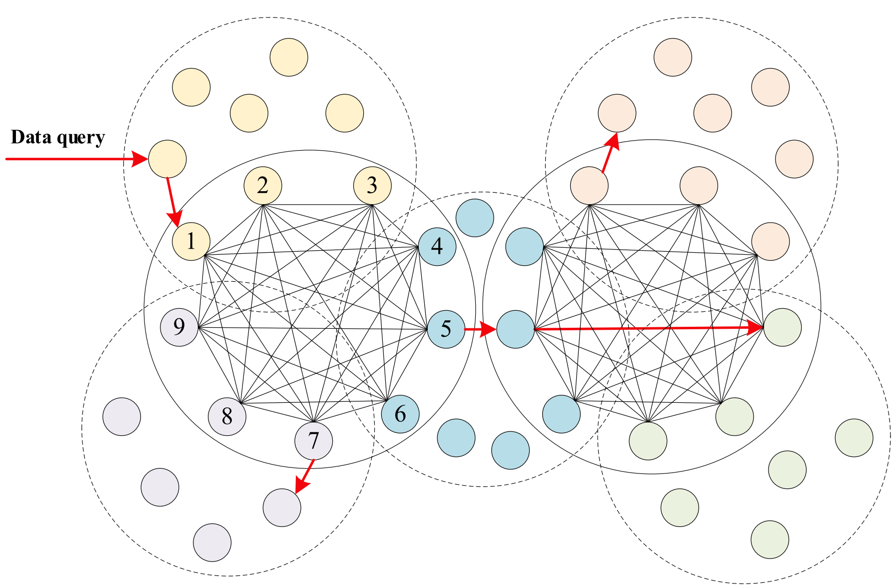


**Fig. 9.** The general plan of data transmission and connection between DTMSs.

(*continued*)

| Algorithm 2: Blockchain-based data transmission between DTMSs |
|---|
| **end for** |
| /* Transmit data */ |
| F(Node$_{set}$) → Node$_p$ |
| Transfer(Node$_p$,Node$_h$,D) |

## 6. Case study

This section develops a data exchange platform between digital twin systems based on blockchain, taking the solid rocket motor manufacturing workshop as the research object. Through the simulation of the whole manufacturing workshop environment, we verify the effectiveness of the connectivity interaction method of the digital twin workshop based on blockchain.

### 6.1. Verification environment

Most of the parts of a solid rocket motor must meet high-performance requirements, such as the rocket motor nozzle, rocket propellant common bottom component, rocket fuel tank wall plate, etc. We will verify the effectiveness of the method in the manufacturing workshop of rocket engine parts. As shown in Fig. 10, a typical manufacturing process of an engine is shown. There will be many different manufacturing models in research and development, which will derive many complexes and different parts specifications. Therefore, the rocket engine parts manufacturing workshop is a typical multi-variety and small-batch manufacturing workshop. Thus, the production line has the corresponding flexibility and manufacturing performance to achieve high-precision and high-efficiency manufacturing in the workshop.

We choose the machining process of each part of the engine to verify the case. The feasibility of the method is demonstrated by constructing the corresponding simulation system. The enterprise has many structural products, and each process is different. In this paper, four kinds of manufacturing parts, namely, the headcover (PTVN10312), the box (PTVM10121), the engine liner shell (PTVA10212) and the diffusion section (PTVL10111), are processed in a certain period. According to the production data of the four types of structural parts, the task requirements are shown in Table 4. The equipment conditions are shown in Table 5, including three dedicated function wire-cutting machines and two DMG lathes (DMG CTV160). Their functions are relatively single, and the others are multi-functional digital control machines.

The following will be based on the above parts and manufacturing technology to verify the proposed method. We have developed the blockchain-based data transmission system and its condition monitoring system. The blockchain verification environment is built with Hyperledger Fabric architecture. The client node is a typical commercial computer configured with an i7-7700 quad-core processor, 8G memory, and 1 T hard disk, which is used to simulate the node sent tasks by the workshop. The server node uses Alibaba Cloud virtual server to simulate the data transmission process of the cloud manufacturing service platform. By default, the accounting node server is configured with three servers, the model is an 8-core 32G elastic compute service (g5), and the bandwidth is 200Mbps. The display software adopts node environment, vS code development software, and Vue.js framework. The display system has two parts: the blockchain generation system of edge pool, and the monitoring system of workshop load status.

### 6.2. Method validation

In the workshop data transmission system, the process of data interaction is simulated. We set up a cloud and divided 18 machines into three edge pools. Furthermore, set a certain bandwidth limit. Through the manufacturing technology in Table 4, we continuously assign different or the same manufacturing tasks in the "cloud" to simulate the task generation in the workshop. The system will adaptively generate the corresponding data by simulating the machine tool working state. Besides, we monitor the bandwidth of the workshop based on the blockchain to verify the feasibility. The specific transmission logic is shown in Fig. 11.

First, each edge pool generates a main blockchain for the manufacturing process. Each edge node of the edge pool will participate in the manufacturing process and generate a sub-blockchain. The central manufacturing tasks and operations of each part are recorded on the block. According to the time stamp, these interactive data are linked together to form a blockchain in chronological order. Therefore, a data management platform is built to manage digital twin data. The data management platform can be accessed through the authorization of each

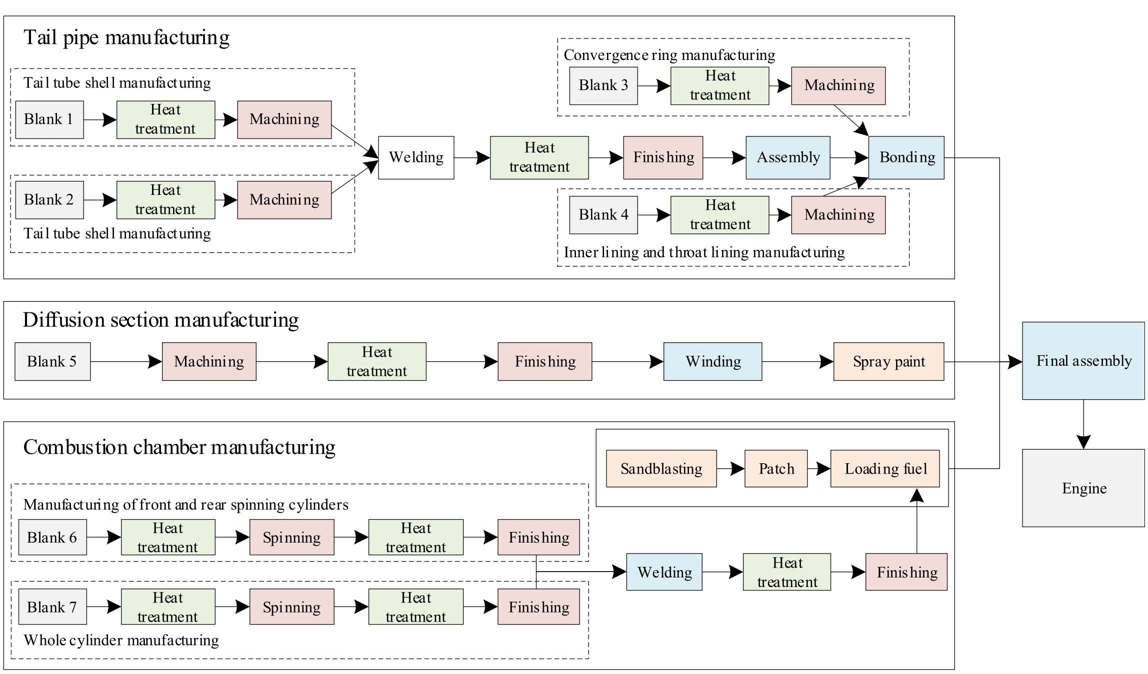


**Fig. 10.** The manufacturing process of solid rocket motor.

**Table 4**
process requirements.

| Name of parts | Quantity | Manufacturing process | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Procedure 1 | | Procedure 2 | | Procedure 3 | | Procedure 4 | | Procedure 5 | | Procedure 6 | |
| | | Name | Time/h | Name | Time/h | Name | Time/h | Name | Time/h | Name | Time/h | Name | Time/h |
| PTVA10212 | 8 | Milling | 2 | Heat-treatment | 3 | Wire cutting | 2 | Finishing Milling | 3 | Finishing turning | 2 | | |
| PTVN10312 | 10 | Rough turning | 1.5 | heat-treatment | 2 | Finishing turning | 2 | Rough milling | 2 | Finishing Milling | 3 | | |
| PTVL10111 | 10 | Milling | 2 | heat-treatment | 3 | Wire cutting | 4 | Rough turning | 1.5 | Finishing Milling | 4 | Finishing turning | 2 |
| PTVM10121 | 8 | Rough turning | 1 | heat-treatment | 2 | Finishing turning | 2 | Finishing Milling | 3 | | | | |

**Table 5**
List of equipment.

| Serial number | Name | Identification | Function |
|---|---|---|---|
| 1 | DMG DMU50 | DMU50-1 | Machining center |
| 2 | DMG DMU50 | DMU50-2 | Machining center |
| 3 | DMG DMU50 | DMU50-3 | Machining center |
| 4 | DMG CTXbeta1250 | CTXbeta-1 | Turning/ Milling |
| 5 | DMG CTXbeta1250 | CTXbeta-2 | Turning / Milling |
| 6 | DMG CTXbeta1250 | CTXbeta-3 | Turning / Milling |
| 7 | CUT220 | CUT220-1 | Wire cutting |
| 8 | CUT220 | CUT220-2 | Wire cutting |
| 9 | CUT220 | CUT220-3 | Wire cutting |
| 10 | DMG CTV160 | CTV160-1 | Turning |
| 11 | DMG CTV160 | CTV160-2 | Turning |
| 12 | DMG DMU60monoBLOCK | DMU60-1 | Machining center |
| 13 | DMG DMU60monoBLOCK | DMU60-2 | Machining center |
| 14 | DMG CTXgamma1250TCLinear | CTXgamma-1 | Turning / Milling |
| 15 | DMG CTXgamma1250TCLinear | CTXgamma-2 | Turning / Milling |
| 16 | DMG MILLTAP700 | MILLTAP700-1 | Milling / Drilling |
| 17 | DMG MILLTAP700 | MILLTAP700-2 | Milling / Drilling |
| 18 | DMG MILLTAP700 | MILLTAP700-3 | Milling / Drilling |

edge node. After clicking the block number of the blockchain, detailed information about the block is displayed, including the block height (block number), transactions stored in the block, and the digger of the block.

As shown in Fig. 12, the blockchain query system provides transaction hash, status, and other necessary information. Therefore, we can query the block information in an edge pool through the query system.

Besides, in the data based on the blockchain, the workshop status information is returned. Based on the smart contract, the manufacturing status load system can be developed through the authority. Fig. 13 shows the number of equipment and the load status in the current edge pool. Simultaneously, some of the states establishing interaction with other nodes are also recorded in the block. Of course, the monitoring system has an inevitable delay because of the consensus time of the blockchain.

Workshop monitoring status, as shown above, can ensure that all nodes participate in the interaction of the whole manufacturing process. Secondly, the proposed data interaction mode can make all nodes become an internal shared data storage system. Based on the above case part, we have created two parts to the method. One part is based on the cloud as the data transmission mode while arranging the corresponding transmission tasks. Their network status comparison is as follows:

It can be seen from the above that for the same task, the efficiency of data transmission is improved based on the blockchain interaction mode, and the whole production cycle is shortened to a certain extent. The cloud edge collaborative workshop based on blockchain has a lower cloud load and higher utilization rate of edge nodes than traditional methods.

### 6.3. Discussions

Previous studies have some limitations. First, the data transmission efficiency is not high due to the information blocking between digital twin systems. The bandwidth explosion problem is prone to occur in the application of cloud-based data interaction methods in the interaction of digital twin systems. To improve data transmission efficiency, the method proposed in this paper establishes a manufacturing node for each digital twin system to form a regional autonomous mode. In summary, the proposed method has the following improvements compared with previous studies.

(1) As shown in Fig. 13, the proposed method can effectively realize the peer-to-peer data interaction in the edge pool;

(2) As shown in Fig. 12, the proposed method can adaptively conduct secure edge nodes self-organization interaction through protocols;

(3) As shown in Table 6, the proposed method can reduce the production time;

(4) As shown in Table 7, the self-circulation of multi-digital twins dramatically reduces the dependence on the cloud and solves bandwidth congestion.

Therefore, the proposed can reduce the pressure of the core network and improve the interaction efficiency between the DTMSs. Simultaneously, DTMS can carry out data exchange operations through blockchain for task cooperation.

## 7. Conclusion

The customized production workshop is a multi-variety and small-batch production workshop with high requirements for flexibility and automation. The DTMS can effectively realize the precise control of product quality during the manufacturing process. However, the DTMS is very dependent on data, especially the actual geometric model of the product. Information blocking will lead to repeated product modeling in each station, which will seriously affect the production efficiency of the workshop. Cloud manufacturing provides a data exchange solution for DTMSs. However, due to the massive amount of data demand, there will be bandwidth congestion and transmission delay if transmitted through the cloud. Aiming at the problem of data demand of DTMSs during multi-variety and small-batch manufacturing processes, this paper

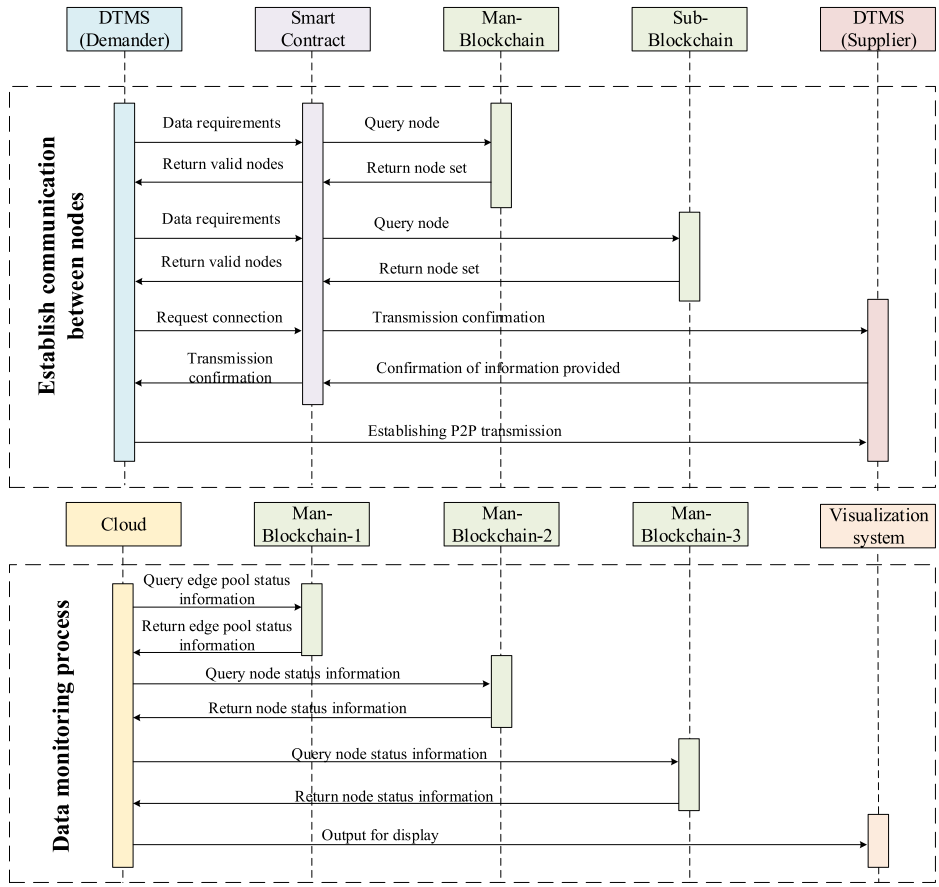


**Fig. 11.** Data transmission and interaction process.

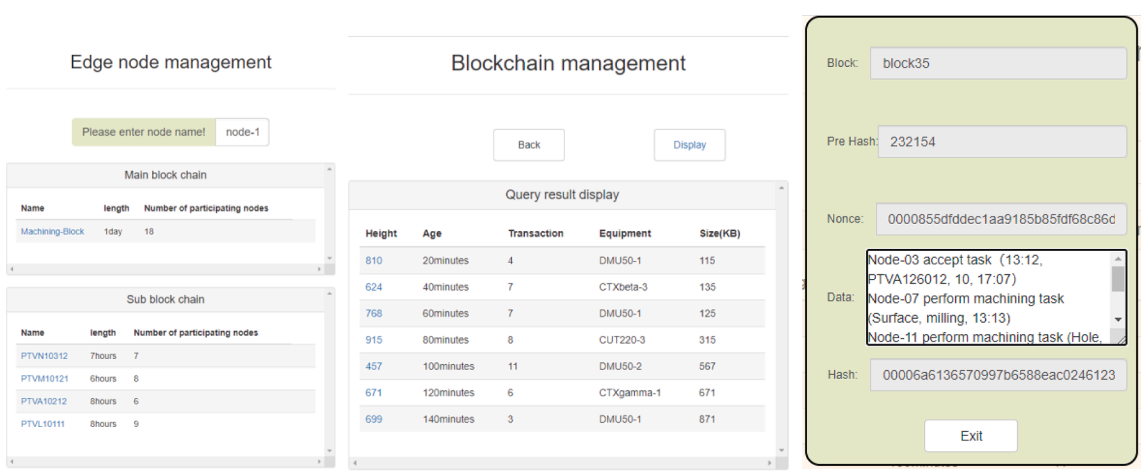


**Fig. 12.** The blockchain-based query system.

explores the architecture of the cloud-edge interplay workshop. It gives the generation method of manufacturing edge pool. Besides, the blockchain-based collaboration method between DTMSs is proposed. The critical contributions are as follows:

(1) This paper constructs a cloud-edge interplay workshop to reduce the pressure of the core network and improve the interaction efficiency between the DTMSs;

(2) The blockchain-based method is studied to assist the DTMSs in data exchange.

The method is verified in a manufacturing workshop simulation system of mechanical manufacturing enterprises. The experimental results show some findings as follows.

(1) The consensus mechanism of POW, and smart contract can realize the adaptive information transmission between multiple stations, which alleviates the current situation of cloud transmission congestion.

(2) blockchain-based connectivity interaction mechanism of DTMSs can meet the data requirements of the DTMSs.

(3) blockchain-based discrete organization model has the potential to help the workshop obtain higher flexibility than before.

However, the proposed method still has room for optimization. Therefore, future research directions include the following specific parts.

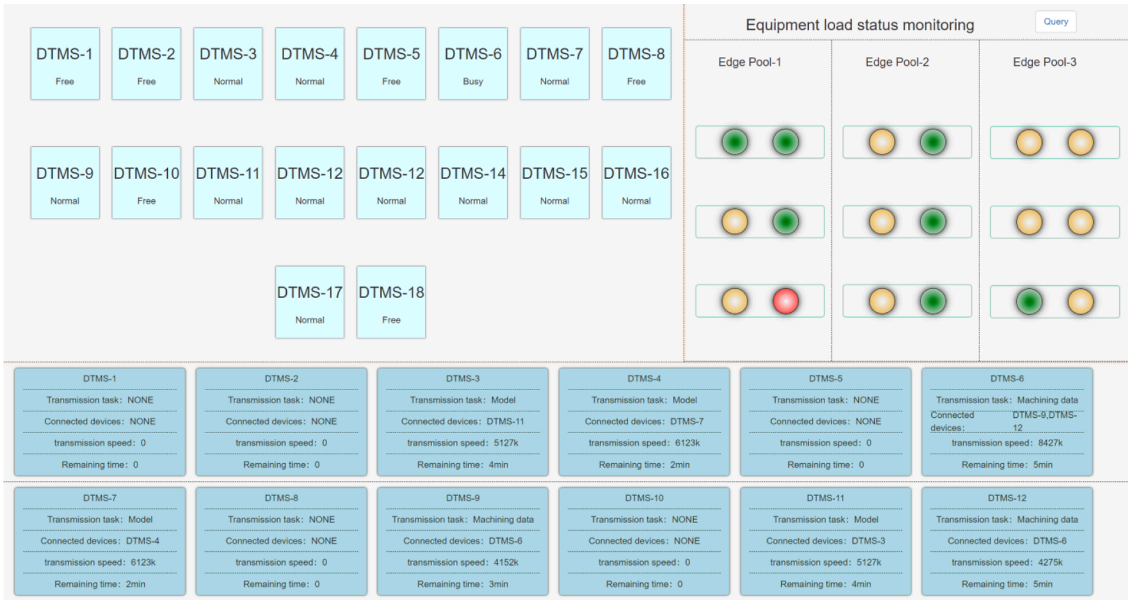


**Fig. 13.** Workshop monitoring system.

**Table 6**
The comparison of time cost.

| Type | Station | Production time/min | Data transmission time/min |
|---|---|---|---|
| Traditional method | DTMS-1 | 96 | 10 |
| | DTMS-2 | 105 | 19 |
| | DTMS-3 | 125 | 11 |
| Blockchain-based method | DTMS-1 | 92 | 6 |
| | DTMS-2 | 97 | 11 |
| | DTMS-3 | 121 | 7 |

**Table 7**
The comparison of load status.

| Type | Time | Cloud average load | Edge average load condition |
|---|---|---|---|
| Traditional cloud manufacturing | 9:00–11:00 | 17.5 M/s\|20 M/s | 7.5 M/s\|20 M/s |
| | 13:00–15:00 | 16.7 M/s\|20 M/s | 6.7 M/s\|20 M/s |
| | 15:00–17:00 | 18.3 M/s\|20 M/s | 8.3 M/s\|20 M/s |
| Blockchain-based cloud-edge collaborative manufacturing | 9:00–11:00 | 7.5 M/s\|20 M/s | 17.5 M/s\|20 M/s |
| | 13:00–15:00 | 16.7 M/s\|20 M/s | 16.7 M/s\|20 M/s |
| | 15:00–17:00 | 8.3 M/s\|20 M/s | 18.3 M/s\|20 M/s |

(1) The proposed method only considers the transmission mode between DTMSs, focusing on machining and assembly. Therefore, the data exchange method under multiple complex processes needs further study.

(2) According to the dynamic manufacturing requirements, it is also a valuable research point to further improve the overall information transmission efficiency from the perspective of system engineering.

(3) In the discrete organization mode, it is equally valuable to study job shop scheduling and adaptive organization methods to improve manufacturing efficiency and economic benefits.

## CRediT authorship contribution statement

**Shimin Liu:** Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing, Resources, Data curation, Visualization. **Yuqian Lu:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Jie Li:** Conceptualization, Methodology, Supervision. **Xingwang Shen:** Software, Visualization, Validation. **Xuemin Sun:** Conceptualization, Methodology. **Jinsong Bao:** Supervision, Project administration, Funding acquisition.

## Declaration of Competing Interest

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

## Data availability

Data will be made available on request.

## Acknowledgments

This work is financially supported in part by the National Key Research and Development Plan of China (Grant 2019YFB1706300), and in part by the Fundamental Research Funds for the Central Universities and Graduate Student Innovation Fund of Donghua University (Grant No. CUSF-DH-D-2020056), in part by Fundamental Research Funds for the Central Universities (No. 2232019D3-32), and in part by Shanghai Sailing Program (19YF1401600).

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