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imseStudio: blockchain-enabled secure digital twin platform for service manufacturing

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ABSTRACT
The manufacturing industry is experiencing a service-oriented transformation in the digitalisation era. However, many small and middle enterprises (SMEs) still rely on traditional manufacturing patterns in which they can hardly servitise manufacturing resources due to the limited budget and poor digitalisation capability. To servitise manufacturing resources, this paper proposes unified five-layer blockchain-enabled secure digital twin platform architecture, followed by its core enabling components and technologies. Firstly, a service-oriented digital twinning model is developed to transform physical resources into digital services. Secondly, a rule-based off-chain matching mechanism is designed to bridge customers' orders with manufacturing services. Thirdly, service-oriented architecture (SOA) is adopted as the major methodology to design and develop the whole blockchain platform. Four blockchain frontend services are developed using React.js, whilst the blockchain backend is developed using private Ethereum blockchain and InterPlanetary File System (IPFS). Finally, an experimental case is conducted based on the 3D printing scenario to verify the effectiveness and efficiency of the proposed platform, named imseStudio. The results show that it not only provides an effective solution to digitalise manufacturing resources but also promotes the transformation towards service manufacturing.

Highlights

- Blockchain-enabled secure digital twin platform is developed to servitise manufacturing resources
- Service-oriented digital twinning model is developed to transform physical resources into digital services
- Rule-based off-chain matching mechanism is built to bridge customers' orders with 3D printer
- Four blockchain explorers are developed to facilitate 3D printing services

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Blockchain; digital twin; service manufacturing; 3D printing service

1. Introduction

The manufacturing industry is experiencing a service-oriented transformation (Kusiak 2019). Driven by diverse customer demands and advanced digitalisation technologies (Gao et al. 2009; Gebauer et al. 2012), this transformation is recognised as service manufacturing. Differing from a traditional 'product-centric', service manufacturing focuses on 'customer-centric' strategies characterised as open, share, high-efficiency, etc. It brings benefits such as greater utilisation of dispersed manufacturing resources, quicker fulfillment of diverse customers' requirements, more environmental friendliness and economic values (Kusiak 2020).

Previous research shares similar concepts related to service manufacturing, such as service-oriented manufacturing, servitisation, product-service systems, manufacturing as a service, etc. For example, early in 1993, Fry et al. proposed a service-oriented manufacturing strategy using the available capacity to meet demand rather than inventories (Fry, Steele, and Saladin 1993). Servitisation, coined by Vandermerwe and Rada (1988), is now widely regarded as the manufacturing strategy transformation from a product-based model into a service-based model (Rymaszewska, Helo, and Gunasekaran 2017). With the development of digitalisation and information technologies, product-service systems are proposed by combining

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services and products to provide a comprehensive product lifecycle solution (Gao et al. 2009; Annarelli, Battistella, and Nonino 2016). Based on cloud technologies, Tao et al. offered manufacturing as service architecture for service virtualisation, composition and selection (Tao et al. 2012; Tao and Qi 2017). These studies exhibit great benefits in facilitating the transformation towards service manufacturing.

However, the success stories of a service-oriented transformation could only be well known from large manufacturing companies with strong financial and technical supports, such as IBM, Rolls Royce Aerospace, Siemens and Xerox (Cavalieri et al. 2017). Many SMEs still face obstacles towards service manufacturing due to its various intrinsic attributes.

- *Limited budget and investment*. According to McKinsey and Company's survey, many SMEs have digital service implementation challenges due to limited budgets and enterprise scales (Albaz et al. 2020). This is because digitalisation often requires a high initial investment and continuous maintenance cost to implement an integrated service solution with advanced technologies, such as digital twin, Internet of Things, etc.
- *Poor digitalisation capability*. Different SMEs have numerous heterogeneous physical resources and expertise, such as machines, materials, workforce, etc. Due to the lack of digitalisation expertise, it is challenging to uniformly servitise these diverse manufacturing resources since they usually have various representations in properties, functions, interfaces, input/output data formats, etc.
- *Insufficient trust and collaboration*. Traditional manufacturing enterprise information systems are designed based on the centralised system framework (Li, Wang, et al. 2018). The information is captured and stored by a small group of parties. According to Fu, Han, and Huo (2017), trust and relationship commitment has significantly favourable effects on service sharing and collaboration. Due to trade secrets, regional policies and many other security issues, the centralised framework is difficult to develop trust amongst stakeholders. Service sharing and collaboration remain superficial and limited amongst SMEs.

In order to address these challenges, this paper proposes a blockchain-enabled secure digital twin platform to facilitate SMEs' service-oriented manufacturing transformation named imseStudio. Compared with traditional manufacturing systems, this paper focuses on providing a decentralised framework combining blockchain and a digital twin as the enabling technologies (Lanza et al. 2019; Mourtzis, Doukas, and Psarommatis 2012). Digital twin, which is the virtual object of the tangibles and intangibles of service manufacturing through data and model, could servitise the manufacturing capacity/status into digital representation (Qi et al. 2018). This requires the adoption of Internet of Things such as real-time sensing and communication technologies to perform digital twinning processes of service manufacturing. Moreover, a secure environment is required to store digital twins and perform trustable operations, which is implemented using blockchain technology. Hence, the objectives of this paper are unfolded into four aspects:

- To propose a blockchain-enabled secure digital twin platform for facilitating a service-oriented manufacturing transformation in SMEs.
- To develop a service-oriented digital twinning model to transform physical resources into digital services.
- To provide a rule-based off-chain matching mechanism to facilitate the service scheduling amongst the various manufacturers and consumers.
- To establish a blockchain-based trustable and trackable manufacturing environment.

The rest of this paper is organised as follows. Section 2 is the literature review of service manufacturing, blockchain in manufacturing and digital twin in manufacturing. Section 3 presents blockchain-enabled secure digital twin platform architecture, key components and technologies. Section 4 presents the service-oriented implementation and deployment. The case study is presented in Section 5. Section 6 discusses the conclusion and future research.

2. Literature review

Related research is reviewed from scientific databases (Web of Science and Google Scholar) under three aspects: service manufacturing, blockchain in manufacturing and digital twin in manufacturing. The literature search of service manufacturing ranges from 1985 to 2021 using keywords: servitisation and manufacturing, product-service systems and manufacturing and service manufacturing, respectively. For blockchain in manufacturing, the search ranges from 2008 to 2021 using keywords: blockchain and decentralised manufacturing systems, blockchain and cloud/social manufacturing, respectively. The search for digital twin in manufacturing ranges from 2003 to 2021 using keywords: digital twin and manufacturing. As a result, some of the most representative literature is selected and summarised below.

2.1. Service manufacturing

With the development of digitisation technologies and changing customer demands, the concept of service manufacturing is gradually entering the public view (Kusiak 2020). The most common benefit of service manufacturing is increasing the company's service level and keeping a high customer retention rate. It may also bring the opportunity to grow shared manufacturing service (Kusiak 2019).

Many researchers have realised the importance of servitisation to the manufacturing industry since the 1980s (David, Caren, and Benjamin 1989; Quinn, Baruch, and Paquette 1988; Vandermerwe and Rada 1988). Vandermerwe and Rada (1988) firstly created the term servitisation, which is widely regarded as the process of adding services to products to increase product value. Gao et al. (2009) summarised service-oriented manufacturing from business model perspectives, industry insight and technology strength. Gebauer et al. (2012) studied service manufacturing's research status in phenomenon descriptions, explanation building and financial consequences. They also discussed the overall impact of service manufacturing in different processes after being applied. Rymaszewska, Helo, and Gunasekaran (2017) proposed a framework to prove value creation and explored the possibility of developing service manufacturing with IoT technology. Zheng et al. (2019) has conducted a systematic review of smart product-service systems and summarised the tendency and future perspectives, including self-adaptiveness with sustainability, advanced IT infrastructure, human-centric perspectives and circular lifecycle. Kusiak (2019) introduced the basic concepts and technologies of service manufacturing as Manufacturing-as-a-Service. It is also suggested that the emerging service manufacturing will be open, shared, easy to configurable, efficient and democratic (Kusiak 2020; Moghaddam and Nof 2018).

2.2. Blockchain in manufacturing

Blockchain, as Bitcoin's fundamental technology, is a distributed ledger to establish a secure and reliable source of cryptographically secured timestamped transaction records (Nakamoto 2009). It has the advantages such as immutability, traceability, reliability, etc. The blockchain core constructs include shared ledger, consensus, smart contract and tokens/cryptocurrency.

Blockchain has shown its greatest potential to deliver business values in decentralised manufacturing. The concept of decentralised manufacturing refers to a scalable, modular and geographically distributed manufacturing unit, located in proximity to the customer and connected to other manufacturing (Mourtzis and Doukas 2012). To embrace and explore more possibilities of decentralised manufacturing, blockchain constructs and its manufacturing applications are reviewed through insightful literature. For example, Li, Liu, et al. (2018) proposed a blockchain-based cloud manufacturing system to improve knowledge sharing for injection mold redesign. Furthermore, Li, Barenji, and Huang (2018) proposed a blockchain cloud manufacturing system for secure data sharing. To handle the cyber-credit in social manufacturing, Leng et al. (2019) proposed a new decentralised blockchain-driven model, named Makerchain. After the early exploration, more researchers used blockchain-based manufacturing for service composition, collaboration and optimisation (Vatankhah Barenji et al. 2019; Aghamohammadzadeh and Valilai 2020).

2.3. Digital twin in manufacturing

Digital twin is a cutting-edge technology to converge the physical manufacturing space and the digital space to realise a series of smart operations, including smart interconnection, smart interaction, smart control and management (Tao and Zhang 2017). It can reflect the properties, conditions and behaviours using digital models and data on a real-time basis (Haag and Anderl 2018). The most critical components of the digital twin include physical entities, digital models and data connection (Tao and Zhang 2017). Real-time convergence and bidirectional interoperation between physical shop-floor and digital shop-floor are established for production control and optimisation (Ding et al. 2019).

Digital twin is widely adopted for production process control, optimising the tolerances, positioner positions, clamping strategies and welding sequences (Söderberg et al. 2017). A Digital Twin as a Service (DTaaS) paradigm is utilised to transform unique wetlands with considerable advantages, including smart scheduled maintenance, real-time monitoring, remote controlling and predicting functionalities (Aheleroff et al. 2021). Critical information during physical production, such as identity, status, geometry, position and energy, can be captured, mapped and synchronised with the corresponding digital representations in cloud space (Guo et al. 2020). Digital twin is adopted for production process control, optimising the tolerances, positioner positions, clamping strategies and welding sequences (Söderberg et al. 2017).

From the three streams of literature reviewed, three observations are made as follows: (1) the existing literature on service-oriented manufacturing mainly explores the service business model and framework design, which lacks the servitisation implementation for SMEs; (2) existing research on blockchain in manufacturing is still at the infancy stage despite many insightful blockchain framework proposals; (3) despite smart environment created by digital twin applications, secure solution is still needed to meet the service requirements from SMEs To fill this gap, this research aims to illustrate how and in what ways the manufacturing services could be created, interoperated, configurated and executed using blockchain and digital twin technologies. To our best knowledge, this research is conducted as one of the earliest implementations and applications using blockchain and digital twin in service manufacturing industry.

3. imseStudio: blockchain-enabled secure digital twin platform

This section presents the imseStudio from three aspects, including the architecture of imseStudio, service-oriented digital twinning model and rule-based off-chain matching mechanism.

3.1. Architecture of imseStudio

Figure 1 shows the architecture of a blockchain-enabled secure digital twin platform, named imseStudio. The imseStudio demonstrates service manufacturing through 3D printing services. The imseStudio has typical characteristics of service manufacturing, such as opening, sharing and integrating product and service (Lasi et al. 2014). Vertically from the bottom to the top in Figure 1, there are five layers:

- The first physical layer at the bottom includes men, machines, materials and facilities that are basic actors of activities in the 3D printing statue progress. The left to right side depicts kiosk scanning customer to generate customer order, 3D printer and laser-engraver working on the customer order, delivering the finished product through package service and 3rd party logistics service. Simultaneously, typical operating activities are perceived by IoT-enabled smart sensing devices, including temperature sensors, humidity sensors, cameras, industrial wearables, etc.
- The second layer is to conduct smart digitalisation and includes mobile/stationary gateway devices, often extended with IoT sensing devices and wireless transfer protocols (e.g. Wi-Fi, Bluetooth, Zigbee, etc.). Digital twinning model is used for cyber-physical bidirectional interoperation. It includes four components: digital twin definition, digital twin interoperation, digital twin configuration, and digital twin execution.
- The third blockchain-enabled secure Digital (Bes-Digital) layer is a cyber space containing blockchain constructs, digital twins and blockchain explorers. The cyber space is governed through the blockchain constructs. Distributed ledger is a key construct for recording the time series of data blocks/transactions. The consensus protocol is used to keep the blockchain system's consistency, and any transactions will be verified and recorded, which effectively prevents cheating. Other foundational constructs, such as cryptographic algorithms and peer-to-peer (P2P) networks provide an approach to devise a secure environment for digital twin interoperation. Digital twins live above the distributed ledger, which contains digital workers, digital machines, digital materials and orders.
- The fourth service layer provides decision support systems and visualisation tools for participating stakeholders, including customers, printers, matchers and workers. These services are enabled by blockchain explorers, which are developed using smart contracts and web technologies. Four blockchain explorers are designed for the following service purposes respectively: (i) customer explorer enabling customers to place the orders and track the statuses of orders, (ii) printer explorer servitising and managing physical manufacturing resources, including men, machines, materials, IoT devices, etc., (iii) matcher explorer facilitating the schedules between orders and printers, (iv) executer explorer handling cyber-physical interoperations between digital and physical twins, executing the dispatched orders and updating the order status.
- At the top of Figure 1 is the user layer listing key stakeholders in imseStudio scenario. There are four groups of users: (1) customers who have the demands for printing their statues; (2) printers who are the service providers to fulfill the customer demands; (3) matchers who are responsible for matching the customers' orders with 3D printers; (4) workers who are the frontline executers conducting the printing tasks.

3.2. Service-oriented digital twinning model

Digital twinning model is used to convert physical manufacturing resources to digital services. As shown in Figure 2, the digital twinning model can be extended in four aspects, digital twin definition, interoperation, configuration and execution.

3.2.1. Digital twin definition

In imseStudio scenario, there are various physical manufacturing objects (e.g. 3D printers, tools and materials). To make the digital twins of manufacturing objects, it is essential to define these manufacturing objects. The digital representations of manufacturing objects need an appropriate set of information (e.g. asset type, owner, brand, property, value, status, etc.). For example, to make

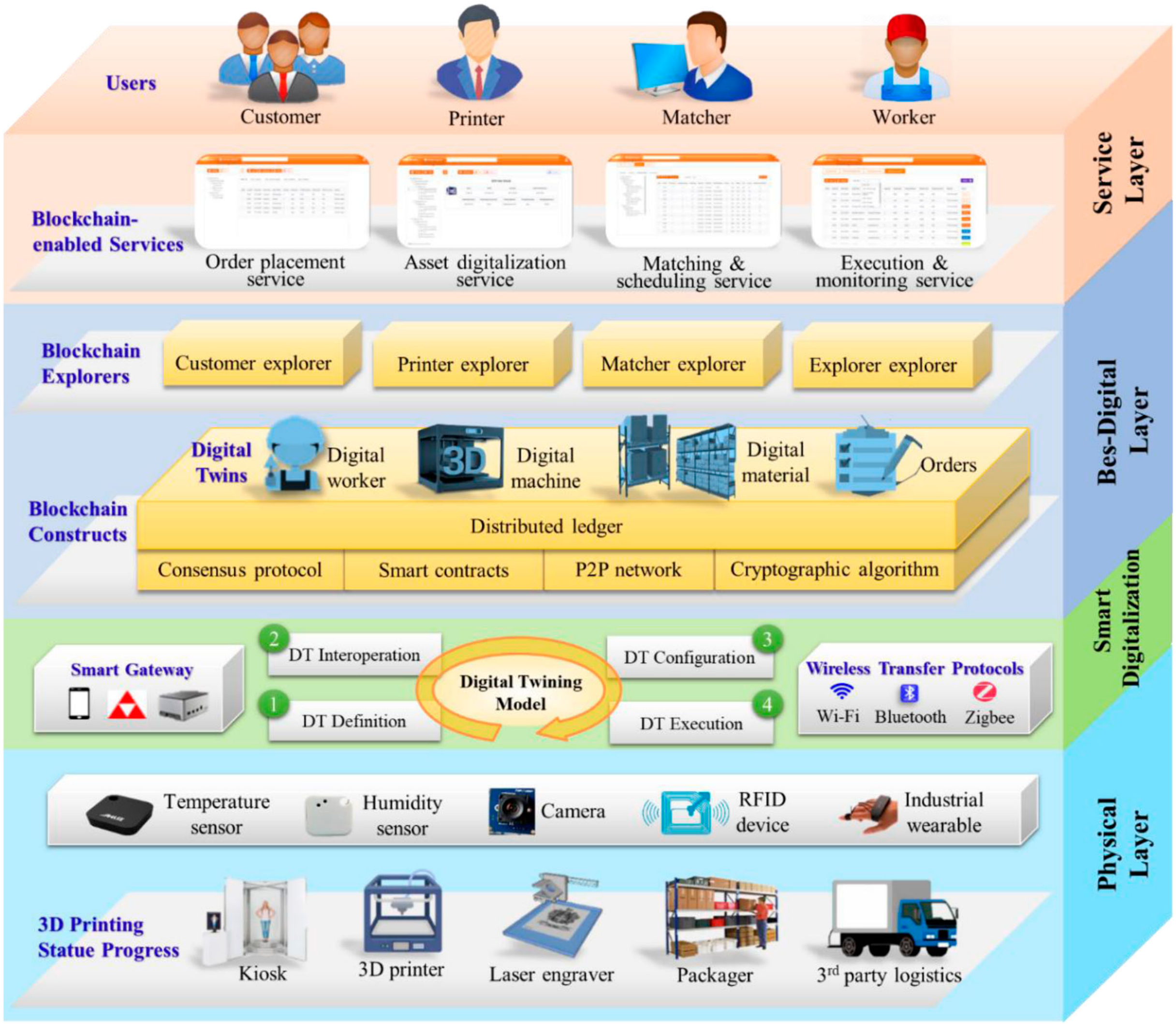

Figure 1. Architecture of blockchain-enabled secure digital twin platform. Architecture of Blockchain-enabled secure digital twin platform with four layers: physical, smart digitalisation, digital and service layers.

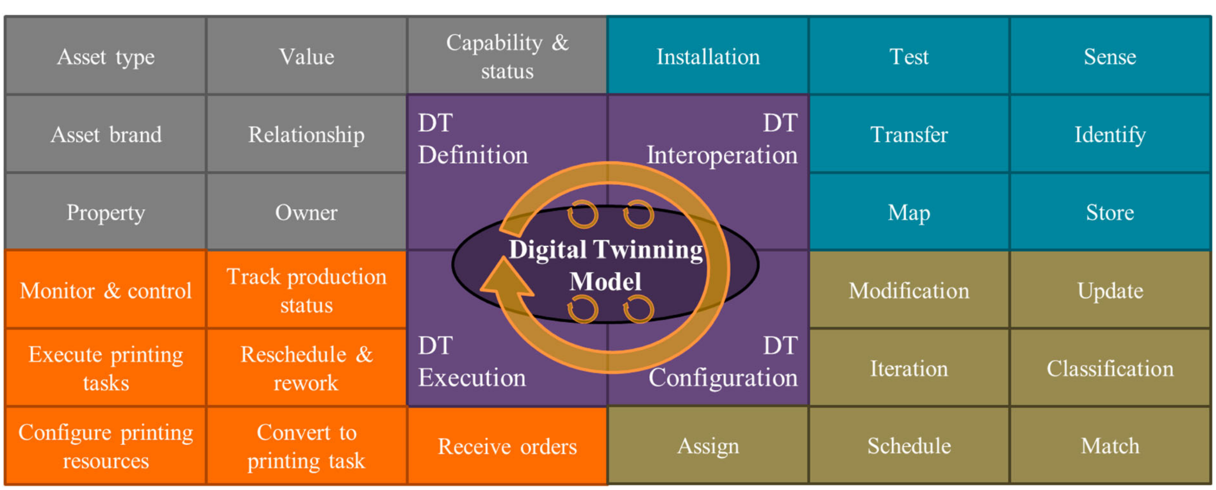

Figure 2. Service-oriented digital twinning model. The digital twining model with four stages: DT definition, DT interoperation, DT configuration and DG execution.

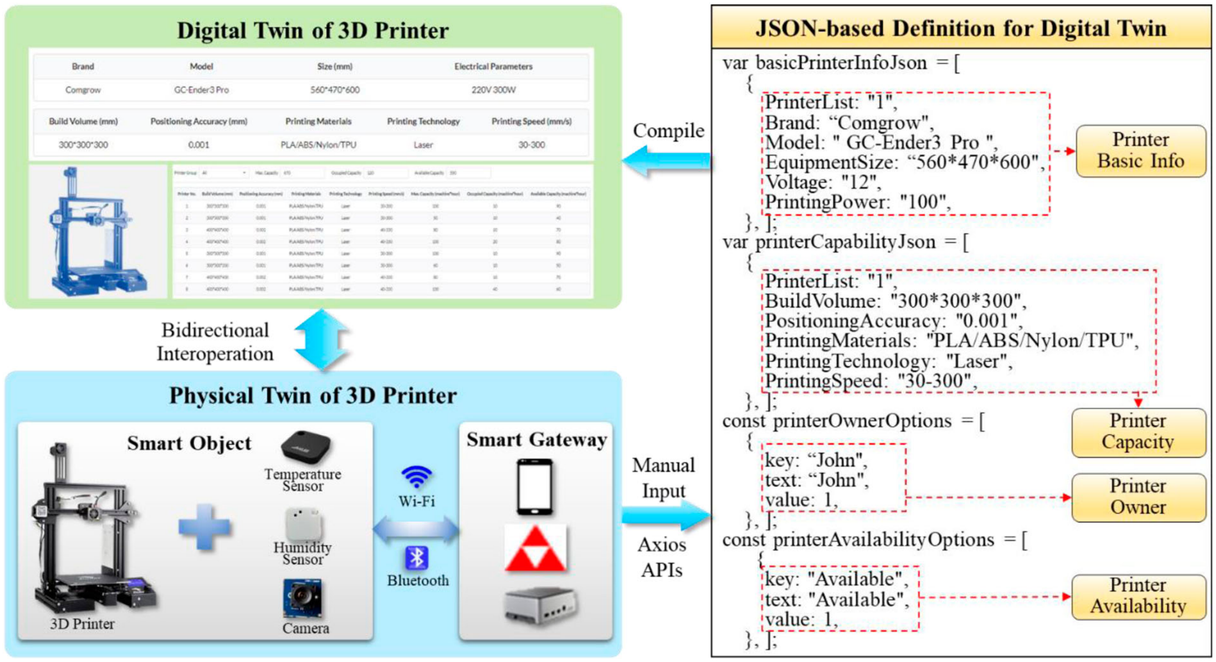

Figure 3. JSON-based definition for digital twin creation. JSON-based data format is used to transform the physical twin into digital twin with example of a 3D printer.

a digital twin of the 3D printer, the asset type needs to confirm firstly as '3D printer', whilst the owner could be input as 'John'. The specific digital representation of the 3D printer is presented in Figure 3. The interactive data/file of the digital representation is JavaScript Object Notation (JSON), which provides a lightweight data-interchange format and flexible structure to extend.

3.2.2. Digital twin interoperation

Digital twin interoperation serves two functions: one is to enable interoperation between physical twin and digital twin, and the other is to provide the interoperation between the digital twins.

- *Interoperation between physical twin and digital twin.* A common technique of bidirectional interoperation between physical assets and digital twins is achieved through smart gateways, such as smart phones and tablet computers. Physical twins which are wearing these sensors are then mapped into a digital platform through the latest technologies, such as Wi-Fi, Bluetooth, etc. Other sensors and devices, such as temperature sensors, humidity sensors, etc., could be installed in 3D printers. Through the smart gateway and wireless transfer protocols, various kinds of physical manufacturing resources are digitalised and managed in a unified digital space.
- *Interoperation between digital twins.* Another type of digital twin interoperation focuses on interoperability between different organisations' digital twins. The Application Programming Interfaces (APIs) (e.g. Axios) could be used to connect the interactions between digital twins from cloud to the blockchain. Through Axios APIs, digital twins from different SMEs could easily collaborate and provide a timely response to customers.

3.2.3. Digital twin configuration

Digital twin configuration represents the management operations of digital twin, such as modification, update, iteration, classification, etc. For example, digital twin owners could modify the digital twin values through the web interfaces (before publishing to blockchain), such as manpower, machine, material, etc. Once a digital twin is published, the owner could update different digital twin versions into the blockchain. Two configuration methods are discussed: manual operation and automatic operation.

- Manual operation refers to the owner changing the values of digital twins' attributes through the interfaces before publishing to blockchain, such as the status, capacity, owner, etc. The updated values could be stored by JSON Patch code. Due to JSON format's flexibility, the updater could flexibly increase the properties to make customised digital twin.
- Automatic operation refers to status synchronisation through IoT. Physical resources (e.g. 3D printers) and the IoT devices create both interconnected and intelligent manufacturing environments.

Table 1. The notations in 3D printing service.

Notation	Definition
T_i	The i-th customer order
P_k	The k-th 3D printer service
u_i	The length of T_i
v_i	The width of T_i
w_i	The height of T_i
U_k	The length of P_k
V_k	The width of P_k
W_k	The height of P_k
m_i	Material type of T_i
M_k	Available material type of P_k
c_i	Colour type of T_i
C_k	Available colour type of P_k
p_i	Required printing accuracy of T_i
P_k	The printing accuracy of P_k

Real-time information could be updated with timestamps through the smart gateway, such as the asset availability and order status.

3.2.4. Digital twin execution

Digital twin execution is illustrated in the 3D printing service. Physical space is used to execute specific production tasks. It contains various physical resources, such as manpower, machines, materials, etc. Digital space contains the digital twins reflecting the physical entities on a real-time basis with multi-dimensional information, including identity, status, location, production progress, and relationship with other entities. The inputs to digital twin execution are prioritised jobs with material requirements, specifications and machine availability. The main outputs are job progresses, material consumptions and finished/WIP statues.

3.3. Rule-based off-chain matching mechanism

Rule-based off-chain matching mechanism refers to the rules built in blockchain explorers, which are used to match and schedule customer orders with 3D printers. The related rule consists of two parts: basic matching rules and advanced scheduling rules. Basic matching conditions refer to the size, material, colour, accuracy constraints, etc.; Table 1 shows the notations in 3D printing services. These attributes are considered as the matching parameters for customer orders and 3D printers. Inspired by Zhou et al. (2018), four attributes of the 3D printing services are considered in imseStudio, including size, material, colour and accuracy. Therefore, we can have the service matching rule as given by the following equations:

$$\min(u_i, v_i) \geq \min(U_k, V_k) \tag{1}$$

$$\max(u_i, v_i) \leq \max(U_k, V_k) \tag{2}$$

$$w_i \leq W_k \tag{3}$$

$$m_i = M_k \tag{4}$$

$$c_i = C_k \tag{5}$$

$$p_i \geq P_k \tag{6}$$

Advanced scheduling rules refer to the conditions to rank the $w_i \leq W_k$ order list, such as customer importance, order priority, first come first serve, delivery date, etc. The advanced rules provide flexible solutions to rank the matched customer orders. Thus, the matcher could match the customer orders with 3D printers by recalling the off-chain rules. For example, once the basic conditions (e.g. size, material, colour and accuracy) are satisfied, the matcher could select predefined rules to rank the matched order list, which provides each printer with an execution plan.

As shown in Table 2, the rule-based off-chain matching mechanism is developed based on the combination of basic matching rules and advanced scheduling rules. The pseudocode is used to demonstrate the matching practices of order priority and customer importance. The inputs are customer orders with varied demands and available 3D printers with varied capacities. The output is the matched plan of orders and 3D printers. In Table 2, i refers to the ith customer order, and I refers to the maximum order number; k refers to the kth 3D printer and K refers to the maximum 3D printer number.

4. Service-oriented implementation based on blockchain

The prototype imseStudio is implemented in the laboratory for demonstration. Service-oriented development based on blockchain, as well as its deployment and configuration, are discussed as follows.

4.1. Service-oriented design and development

The imseStudio is designed as a web-based platform following the SOA design methodology. As shown in Figure 4, the blockchain platform could be divided into four components: blockchain explorers, blockchain information service, Ethereum blockchain network and private IPFS. Following the SOA principles, the development of the four components is comparatively autonomic, whilst RESTful APIs achieve the composition and connection. The relations and information flow amongst the four components are illustrated based on 3D printing scenarios. Inspired by Huang and Mak (2001), the development and deployment environments are presented in Table 3.

Table 2. Rule-based off-chain for matching orders and printers.

Off-chain rule: Matching rule based on order priority and customer importance
Input: Customer orders with varied demands, available 3D printers with varied capacities
Output: The matched plan of orders and 3D printers

For $i = 0$ to I; $k = 1$;
  While $k < = \mathrm{K}$;
    if (min$(U_k, V_k, W_k) \leq Size(u_i, v_i, w_i) \leq$ max(U_k, V_k, W_k)) //size constraint
      if $(m_i = M_k)$ //material constraint
        if () //colour constraint
          if $(a_i \geq A_k)$ //accuracy constraint
          Assign order i to 3D printer k;
          Rank the orders in 3D printer k based on order date;
          Re-rank the orders in 3D printer k based on customer importance;
           break;..
         else $k = k+1$;
        else $k = k+1$;
      else $k = k+1$;
    else $k = k+1$;
End While
  If $k > \mathrm{K}$
    Show an alert and assign order to unmatched orders;
  End If
End For

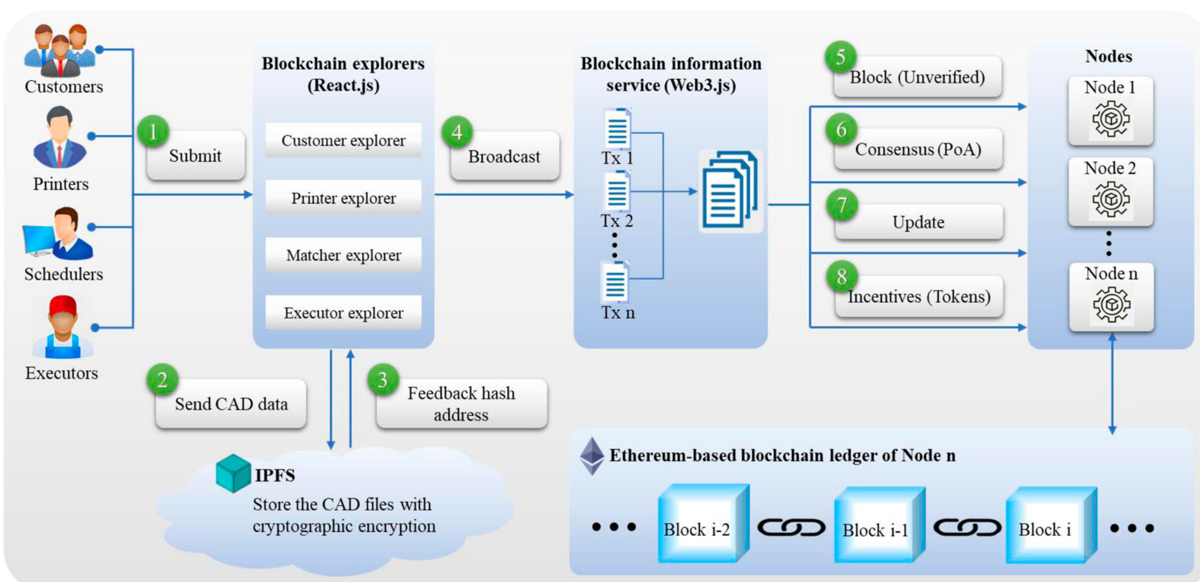

Figure 4. Service-oriented imseStudio implementation. The technical architecture and information flow of imseStudio, including key users, blockchain explorers, blockchain information service, Ethereum blockchain, IPFS.

4.1.1. Blockchain explorers

The blockchain explorers are designed based on the requirement investigation on customers and 3D printing service providers. Four blockchain explorers are developed to meet the customers and the service providers' requirements, including customer explorer, printer explorer, matcher explorer and executer explorer. Customer explorer is designed for customers to place their 3D printing orders and track the printing status. Printer explorer is designed for printers to servitise the manufacturing resources. Matcher explorer is designed for matchers to schedule and assign customer orders to relevant 3D printers. Executor explorer is designed for operators to conduct the printing tasks. React.js, HTML and CSS are used to provide an efficient and modular web-based express architecture. Notably, React.js is a JavaScript library for building user interfaces with the features of reusable components, stable code, strong community, etc.

4.1.2. Blockchain information service

Blockchain information service is placed in the middle of Figure 4. It serves as the middleware role to connect, manage and maintain the physical nodes with blockchain. All the three components can be physically distributed using different servers. The blockchain information service is used to achieve the basic blockchain

Table 3. Development and deployment environment for imseStudio.

Implementation stage	Component	Description
Development	IDE	Visual Studio Code
	IPFS	V0.5.3
	Solidity	V0.5.16
	Front-end programing language	HTML, CSS, React.js
	Library	Web3.js
	Distributed application development	Ganache-2.5.4-win-x64
	Operating system	Windows 10, 64 bits
Configuration and deployment	Customer node	Ubuntu Linux 18.04 (64 bits, 4 CPUs, 4 GB RAM, 40 GB ROM)
	Printer node, matcher node, boot node	Ubuntu Linux 20.04 (64 bits, 4 CPUs, 4 GB RAM, 80 GB ROM)
	Genesis block	Puppeth is used to generate the genesis block
	Consensus algorithm	PoA (new block is generated every 5 s)
	Blockchain environment	Go-Ethereum client

functions, such as digital identity registry, transaction ordering and packaging, broadcast, consensus, etc. Web3.js is used to achieve the interaction between blockchain explorers and blockchain backend by calling the predefined smart contracts. Notably, web3.js is a collection of libraries that allow the users to interact with the local/remote blockchain node using an HTTP connection.

4.1.3. Private IPFS cluster

IPFS is a peer-to-peer file system used to store large-size files, such as CAD files, figures, G-code, etc. To build the private IPFS cluster, the swarm key is firstly used to achieve the local private building. Notably, the swarm key will be referenced in this private network. Secondly, the bootstrap IPFS node is used by client nodes to connect to the private IPFS network. Finally, it needs to start the private IPFS network and limit the node access by configuring the environment variable 'LIBP2P_FORCE_PNET'. The solution uses a private IPFS cluster to store the large-sized files, whilst blockchain is used to store its permalinks/hash address with timestamps, metadata and version information. This combined solution not only saves vast blockchain storage space but also increases the platform performances.

4.1.4. Blockchain platform-specific considerations

Before applying a specific blockchain network, we compare two mainstream blockchain platforms: Ethereum and Hyperledger Fabric, to explorer the suitable blockchain solution in imseStudio. Sajana, Sindhu, and Sethumadhavan (2018) presented a compressive comparison between Ethereum and Hyperledger Fabric. According to the comparison, it is suggested that Ethereum-based blockchain is chosen as the development platform due to the public network. Public network means that the customer/printer could flexibly registry and join imseStudio without centralised authorities. This advantage matches the service manufacturing features, such as openness, sharing, etc. Admittedly, data security might be challenging under public network. Therefore, a combined solution of the Ethereum blockchain and private IPFS cluster is designed and achieved to protect the data security through the access control and hash function.

4.2. Node configuration and deployment

There are four key stakeholders in imseStudio, including customers, 3D printer servicer, matcher and 3D printing executer. The node configuration and deployment of imseStudio are important to affect the security and privacy of key data (e.g. CAD files, customer personal information, etc.).

The second half of Table 3 shows the configuration and deployment environments for imseStudio. Four full nodes are configured in imseStudio for maintaining the block data, which run separately in two Ubuntu Linux servers, namely Ubuntu Linux 18.04 and Ubuntu Linux 20.04. The first node is deployed on Ubuntu Linux 18.04 for all customers to place their orders. The rest three nodes are deployed on Ubuntu Linux 20.04. For instance, the second node is deployed for printers and executers to servitise their manufacturing resources and conduct the printing tasks. The third node is deployed for matchers, similar to the miners competing for the matching opportunity for rewards. The final node is the Boot node, which is used to achieve access right management and connections between different nodes.

Figure 5 presents the five stages to configure the imseStudio. The first stage is to use the puppeth program to generate the genesis block '3dpblockchain.json' and assign authoritative nodes to the initial data in the imseStudio platform. The second stage is to use the go-Ethereum client to create the consortium blockchain nodes based on '3dpblockchain.json'. The third stage is to set the consensus algorithm, in which Proof of Authority (PoA) is selected due to the better performance in transaction speed and throughput. The fourth stage is to use the Boot node for connecting all the nodes and forming the consortium blockchain network. The final stage is to deploy the smart contracts and related applications in the consortium blockchain. After the above steps, imseStudio could be deployed and configured successfully.

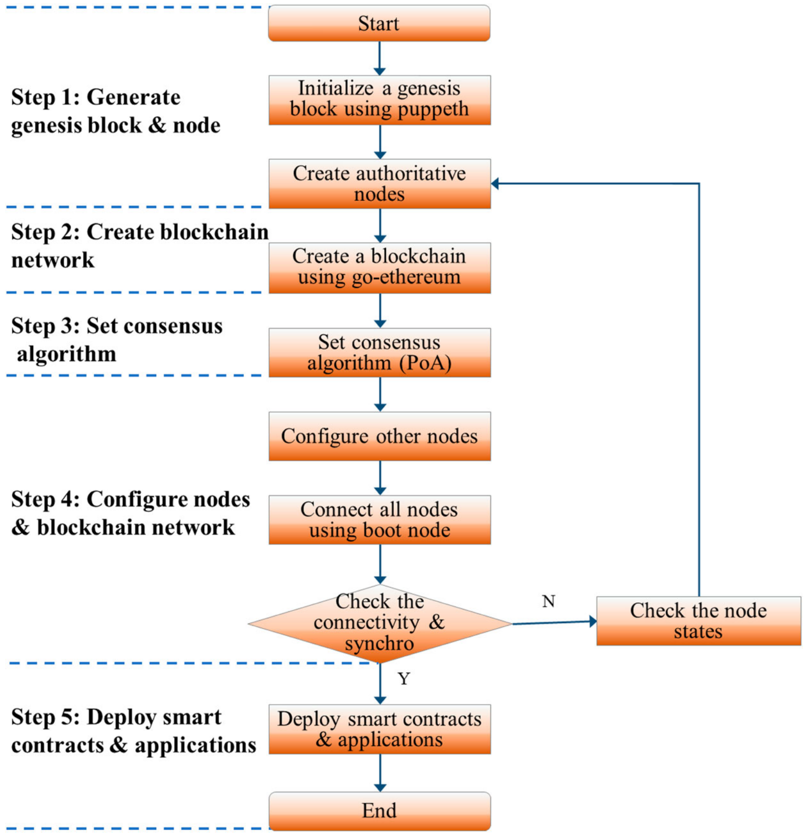

Figure 5. The flowchart of blockchain node configuration and deployment. The flow chart to configure and deploy the blockchain nodes with five steps: genesis block generation, blockchain network creation, consensus setting, nodes and blockchain configuration, smart contracts and applications deployment.

5. Case study

This section presents the case study to demonstrate the effectiveness and efficiency of imseStudio platform. Section 5.1 presents the scenario description of imseStudio. Sections 5.2 and 5.3 illustrate the effectiveness and efficiency of imseStudio. Discussion and limitation are presented in Section 5.4.

5.1. Scenario description

The imseStudio is motivated by an initiative 3D printing company. This company aims to provide customers with 3D printed statues based on 3D scanning and 3D printing technology. As depicted in Figure 6, there are three stages in imseStudio scenario, namely order placement, statue production and the statue delivery. In order placement stage, customers use the 3D scanner/kiosk to generate, edit and place the customer orders. In statue production stage, customer orders need to be matched with the relevant 3D printers, then executed by the frontline workers and supervised by the leaders/managers. In the statue delivery stage, statue delivery could be outsourced to a third-party logistics (3PL) service that will fulfil the statue delivery to the customer. To clarify the research scope, this paper mainly focuses on order placement and production stages, and statue delivery is out of this research content.

Although imseStudio provides a promising solution to meet the customers' demands, it also faces two questions. Firstly, there are diverse physical resources such as 3D printers, laser-engravers, materials, etc. The servitisation of the manufacturing resources must embrace digitalisation (Liu, Zheng, and Xu 2021). Digital twin provides a promising solution to servitise the massive manufacturing resources. Therefore, how could digital twin be used to servitise the manufacturing resources? Secondly, information security is always a concern in digital environments due to potential cyber-attack and interest conflict (Jing et al. 2014). Blockchain has the potential to provide a secure environment due to its nature of immutability, consistency, decentralisation, etc. Therefore, how could blockchain be used to secure the creation, interoperation and execution of digital twins?

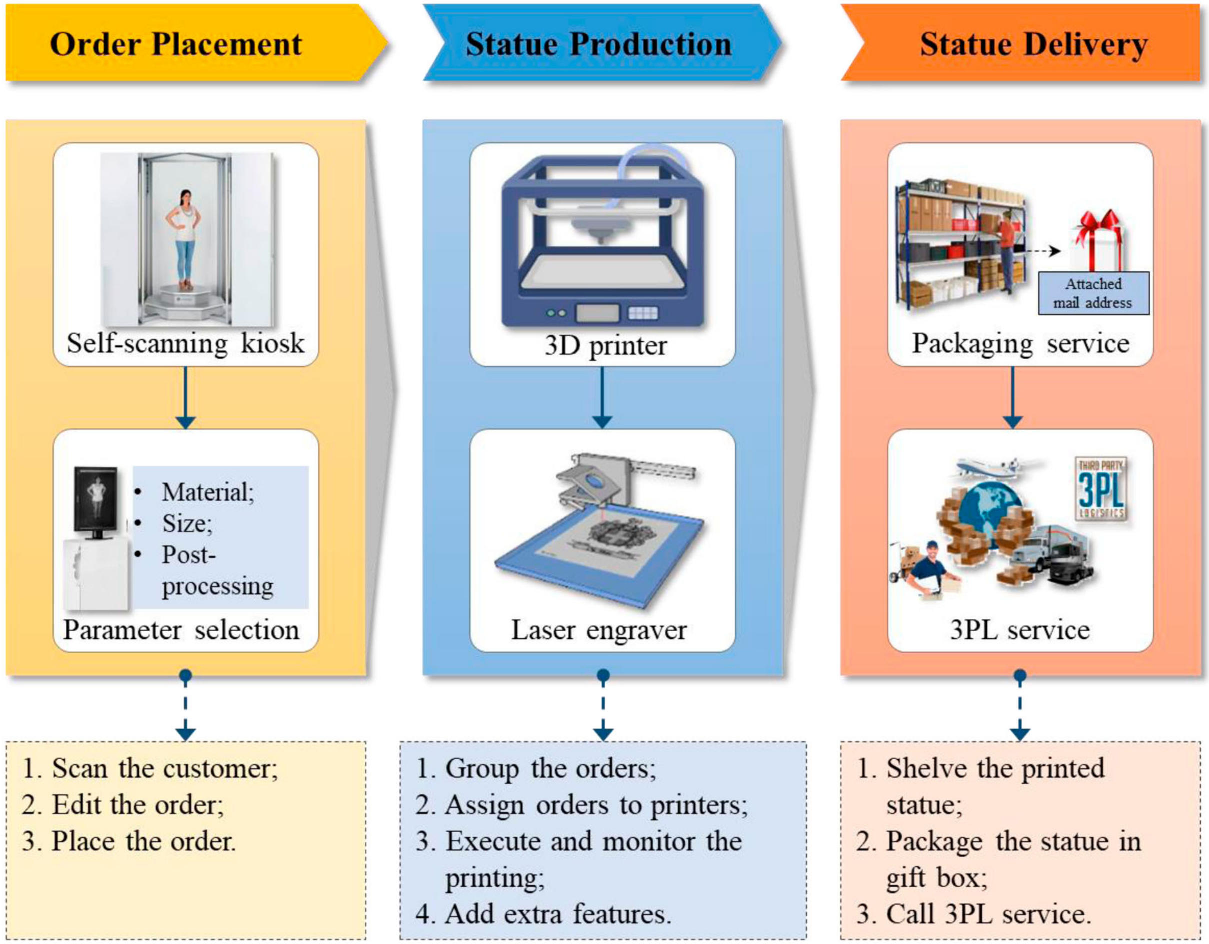

Figure 6. The imseStudio: a solution to make customised statues. The scenario description of imseStudio to make a customised statue from order placement, statue production to statue delivery.

5.2. Blockchain explorers

To illustrate the effectiveness of imseStudio, the subsection discusses four blockchain explorers and the key services, workflows and supporting technologies.

5.2.1. Printer explorer

Figure 7 presents the workflow for 3D printing servicers to servitise their 3D printers using printer explorer. Printer explorer is designed for 3D printing servicers, who could create, update and manage their own 3D printers. There are six steps for 3D printing servicers to conduct asset servitisation:

Step 1: Add new 3D printers. There are two methods to add new 3D printers. One is to connect the 3D printers through HTTP APIs. The other is to connect 3D printers manually by servicers. The main difference is that the APIs method saves time to fill the basic printer information.

Step 2: Fill attribute values. The servicers need to fill the primary 3D printer basic information as defined in JSON format, such as printer brand, picture, cavity size, working voltage, etc.

Step 3: Configure capacity information. The capacity information of 3D printer is filled to describe the 3D printer's working capability, such as available materials, accuracy, etc.

Step 4: Create 3D printing services. After filling in the primary attributes and capacity information, the servicers could servitise the 3D printer in the imseStudio.

Step 5: Confirm publishing services. To publish the new services, the servicers need to select generated new 3D printer services, and confirm every detail before publishing to blockchain.

Step 6: Publish to blockchain. By clicking the 'Publish' button, the process of servitising resources could be finished by sending printing service to blockchain. The results are presented in the Ganache blockchain.

5.2.2. Customer explorer

Figure 8 presents the workflow for customers to place orders using customer explorer. Customer explorer is designed as web services, including order placement service and order status traceability service. There are six steps for customers to finish the order placement:

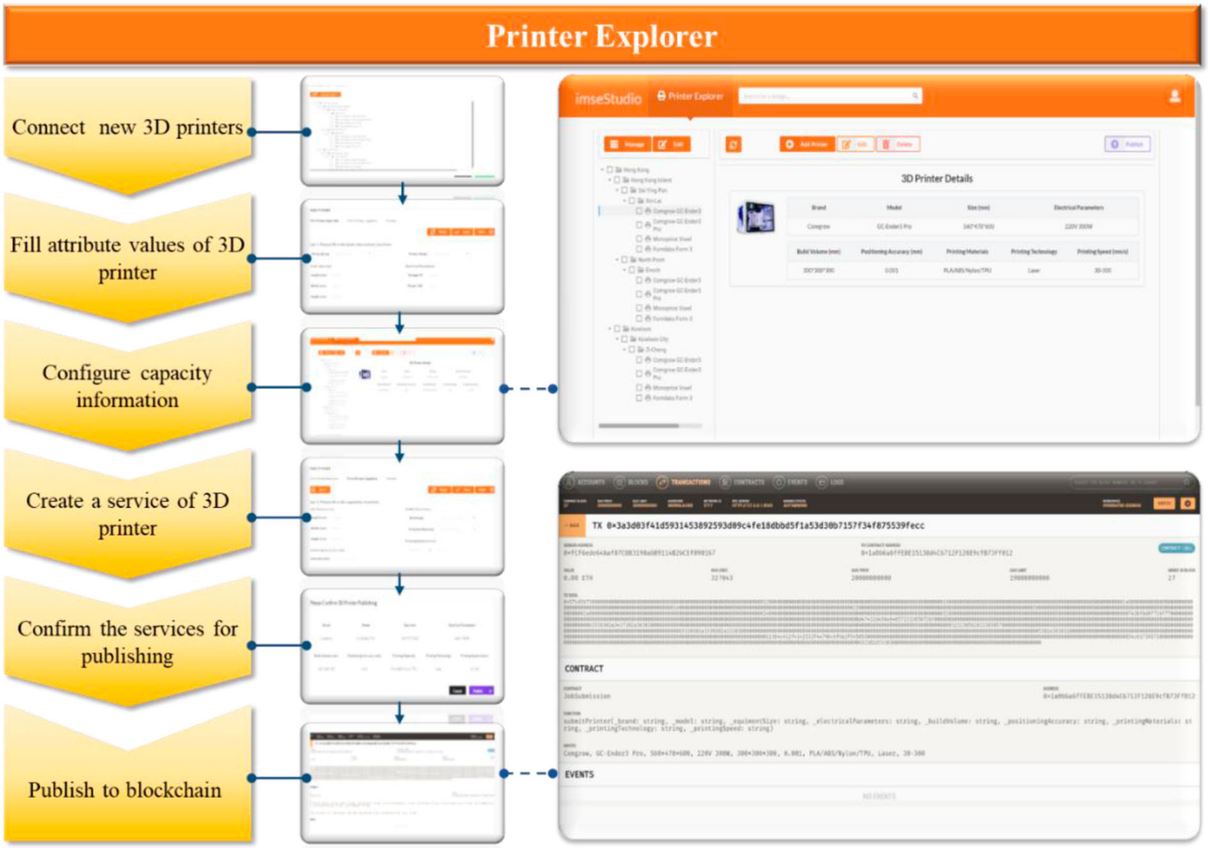

Figure 7. The workflow of printer servitisation through printer explorer. The workflow description to servitise the 3D printer by printer explorer from connecting 3D printer to publishing the digital 3D printer to blockchain.

Step 1: Prepare CAD files. There are two methods to prepare the CAD files: to upload existing CAD files or scan in a kiosk. Figure 8 shows a Yoda in Standard Triangle Language (STL) file uploaded from the existing one.

Step 2: Customise order information. There are two types of customers: common customers and professional customers. The common customers could customise their own uploaded CAD files using default choices including material, colour, size and accuracy, whilst the professional customers could select advanced 'customise' methods to finish the 3D printing parameter settings, such as layer height, infill density, temperature, etc.

Step 3: Add order into the cart. If the customers want to put more different orders or want to purchase them later, they could add the orders into the cart.

Step 4: Fill in the shipping information. The customer could fill in the shipping information to receive the statue.

Step 5: Preview the customer order. To finish the order placement, the customers need to select generated orders and preview the order details before publishing them to blockchain.

Step 6: Publish to blockchain. By clicking the 'Publish' button, the process of order placement is finished by sending the customer orders to blockchain. The results are presented in the Ganache blockchain. Notably, hash value is the unique identification of the Yoda STL file, whilst the Yoda file is stored in IPFS.

5.2.3. Matcher explorer

As shown in Figure 9, matcher explorer is designed for schedulers to assign customer orders to suitable 3D printing services. Both customer orders and 3D printers are retrieved from blockchain, which are published through customer explorer and printer explorer. Notably, MetaMask is used as a tool to manage each user's cryptocurrency account. Currently, the token (cryptocurrency) is used to pay the transaction fees, which helps the stakeholders to upload the information into blockchain. At this stage, matcher is an administrator of the blockchain platform. There are four steps to complete a typical matching and scheduling service: order retrieval, printer retrieval, match and publish.

At the initial phase of order retrieval, the matcher could input the retrieval conditions such as time range, product type, delivery date, etc. Then the matcher needs to generate the G-code from the retrieved orders using Ultimaker Cura. Moreover, the estimated printing time is

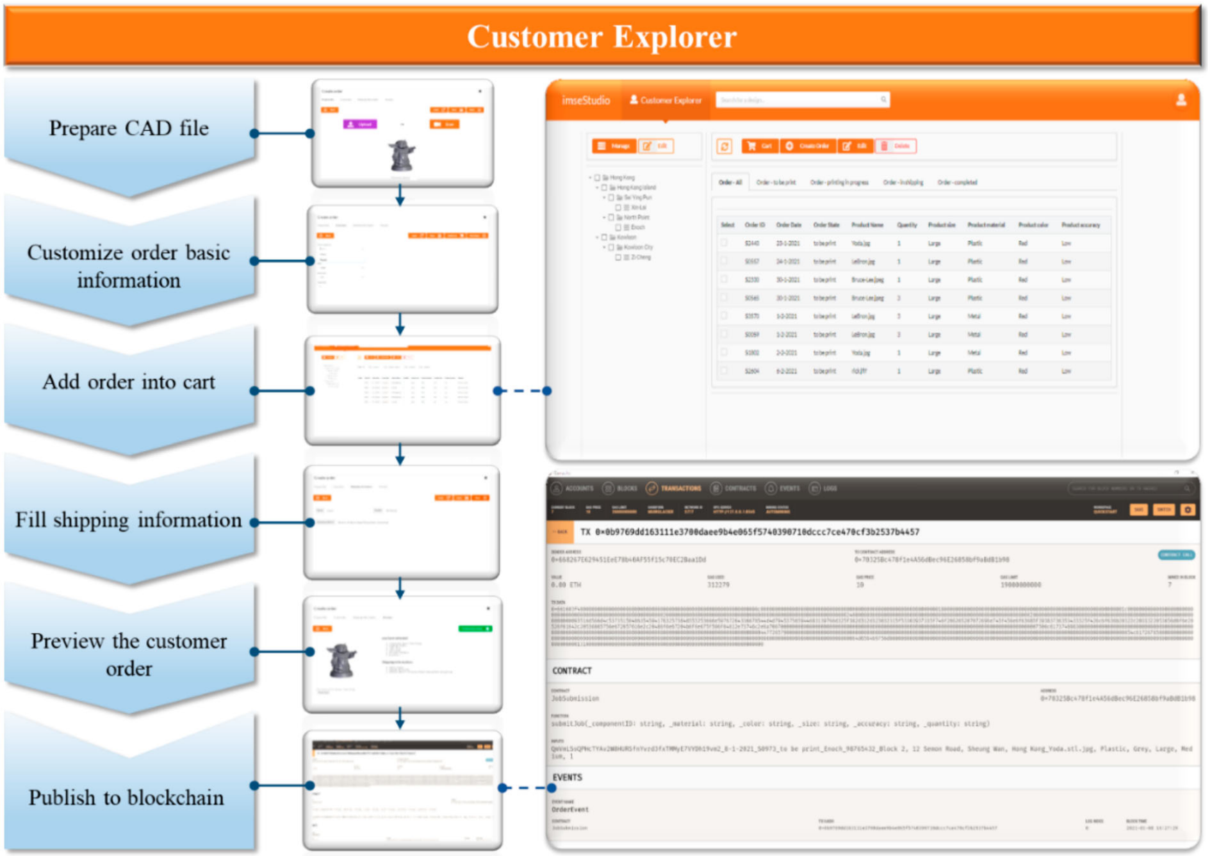

Figure 8. The workflow of order placement through customer explorer. The workflow description to place the customer orders by customer explorer from preparing a CAD file to publishing the customer orders to blockchain.

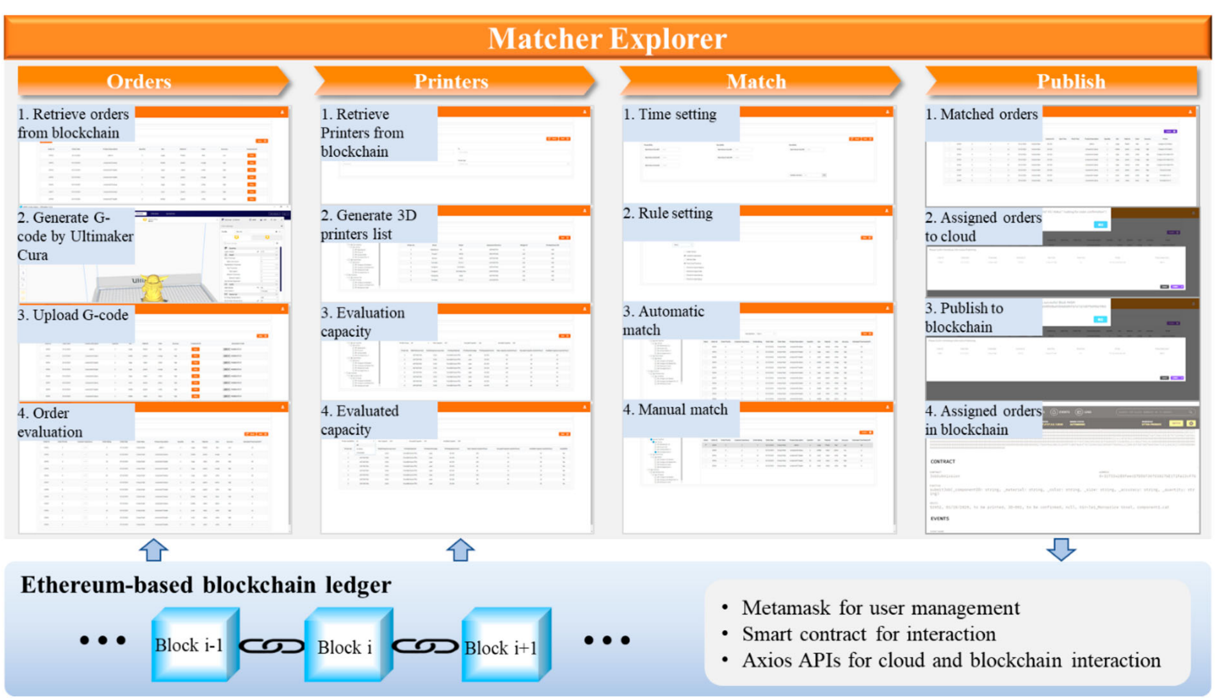

Figure 9. The workflow of matching customer orders with 3D printers. The workflow description to match the customer orders with 3D printers by matcher explorer from order retrieval to publishing the matched results to blockchain.

automatically calculated through Ultimaker Cura based on material type, infill density, accuracy, etc. After uploading the G-code of the customer order, the matcher needs to evaluate the customer's importance. Customer importance is evaluated manually based on the customer types, such as common customer, VIP customer. The evaluated orders will be re-ranked based on the order rating scores which are calculated based on order priority and customer importance.

Then the 3D printers could be retrieved based on the conditions such as printer type, location, etc. Capacity evaluation will be conducted based on the available working time in the printer list. The matcher could set the availability rate of the working time threshold (e.g. 50%). If the available working rate is larger than 50%, the 3D printer could be selected to assign customer orders.

At the match stage, the time window needs to be set to determine the job shifts, as shown in Figure 9 (Match-1). Rule setting is used to call different version rules to finish the automatic matching and scheduling, including order priority, customer importance, delivery date, etc. The matcher could also define new rules in matcher explorer and achieve flexible match and schedule. For example, the matcher could define a new rule as 'Rule 1' based on customer importance. Then 'Rule 1' could be used in automatic matching between customer orders and available 3D printers. Manual match is used to assign unmatched orders to relevant 3D printers based on expert knowledge.

The final step is to publish the matched results to blockchain. The matcher first needs to check each matched orders and 3D printers. After confirmation, the matcher could select relevant matched results and click the 'Publish' button. If the printers have a cloud-based solution, the results will be sent to the printers' cloud environment directly and published to blockchain. If the printers have no cloud-based solution, the printers could use the executer explorer to conduct printing execution processes.

5.2.4. Executer explorer

Executer explorer is designed for frontline workers to conduct the printing tasks, as shown in Figure 10. There are four stages involved in executer explorer, including printing task, printing configuration, printing execution and monitoring and control.

In the initial stage of the printing task, the printing manager synchronises the orders which are assigned by the matcher. Then the manager transfers the orders to printing tasks based on the quantity, material, accuracy, etc.

In the printing configuration stage, the manager needs to assign the printing tasks to relevant frontline operators. The operator sets up the printer and prepares the materials and tools. For example, the operator checks the availability of a 3D printer, covers the printer base plate using tapes, and chooses the materials and sets parameters based on printing specifications.

In the printing execution stage, the operator will press the 'Start' button using a mobile-app. The start time will be recorded in executer explorer. Depending on the material, accuracy and size, the printing time could be varied from minutes to hours. Simultaneously, monitoring and control are conducted during the execution activities. Once there is any fault or breakdown, the operator could easily click the 'fault report' button, then the printing task will be rescheduled in the task pool with the highest priority. When the printing task is finished, the operator could press the 'Finish' button to record the printed tasks and generate duration. After that, the operator could perform the next tasks.

Finally, all the order states are visualised in the monitoring and control stage, such as 'to be printed', 'printing in progress', 'rework', 'printed'. The managers could supervise the printing activities and adjust the progress flexibly on a real-time basis.

5.3. Performance evaluation of imseStudio

To illustrate the efficiency of imseStudio, the performance analysis is conducted by evaluating two criteria: latency and throughput.

5.3.1. Blockchain infrastructure setup

The experimental infrastructure is HPE-ProLiant DL380 Gen10 server with two virtual machines: Ubuntu Linux 18.04 and 20.04. Ethereum-based blockchain is the backend. Four blockchain nodes are deployed by Go-Ethereum 1.10.3. The consensus mechanism is configured as PoA with every 5 s interval for generating a new block.

5.3.2. Evaluation criteria

Two evaluation criteria are selected for the blockchain performance evaluation: latency and throughput (Liu et al. 2020). Latency refers to the difference between the starting time and completion time of 'publish' or 'retrieve' action. For a set of transactions, the average latency is the average latency of all transactions. Throughput refers to the number of successful transactions per second (tps). Moreover, four types of transactions are used in order to evaluate the imseStudio performance, including printer transactions, order transactions, matcher transactions and execution transactions.

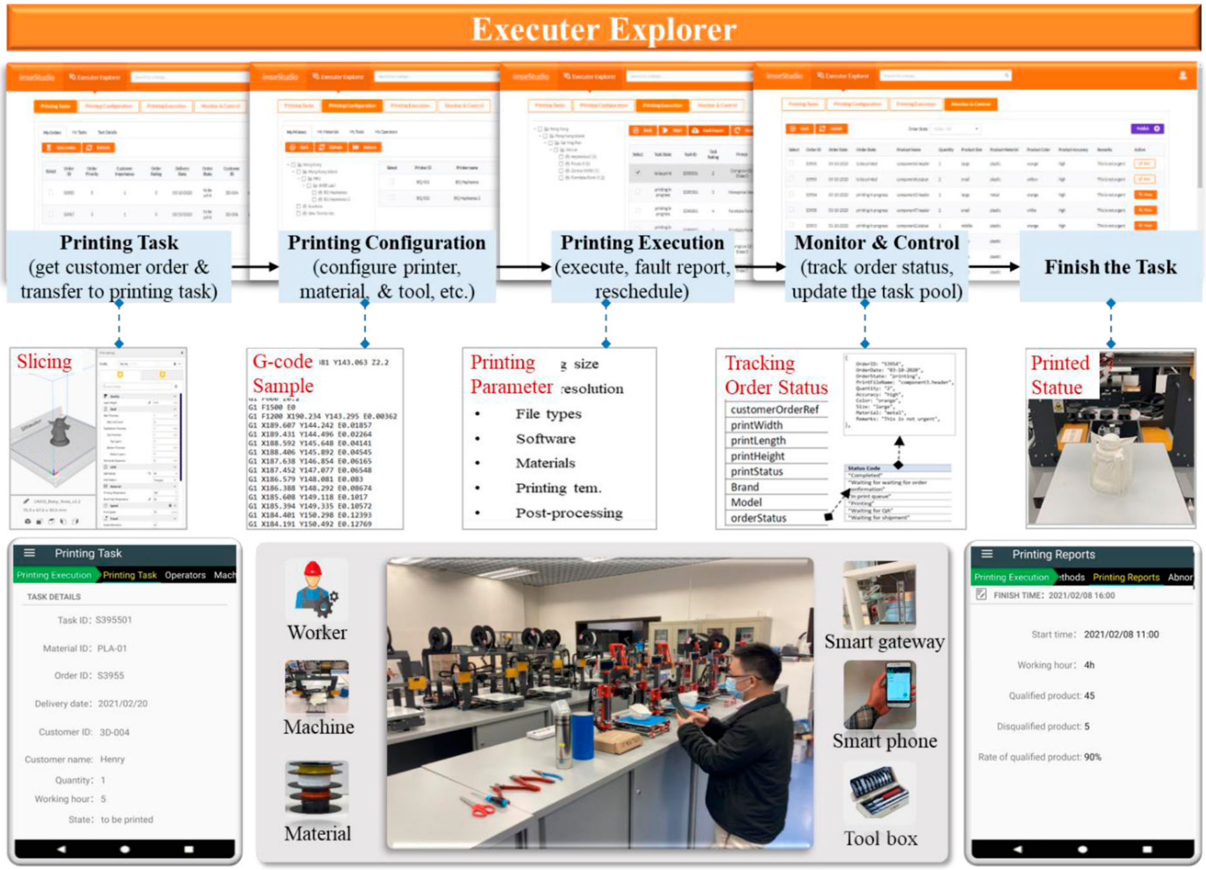

Figure 10. Workflow of printing execution through executer explorer. The workflow description to execute the 3D printing tasks by executer explorer from printing task retrieval to finishing the task.

5.3.3. *Result analysis*

Table 4 presents the experimental latency and throughput results, which prove that imseStudio could work efficiently and practically. In 'Publish' latency evaluation, the average latencies of printer, customer, matcher and executer explorers are 11.28, 14.75, 6.80 and 6.56 s, respectively. These average latencies are calculated by averaging 10 latency values from blockchain explorers to blockchain backend. The results show that the imseStudio could effectively work with considerable efficiency. In 'Retrieve' latency evaluation, printer explorer and customer explorer are set as automatically retrieving from blockchain every 5 s. The matcher explorer and executer explorer are retrieving using the manual method, whose response time is nearly real-time.

For throughput evaluation, the minimum transaction numbers are calculated using Equation (7). In the imseStudio blockchain, the gas limit is designed as 21,000 gas, whilst the block gas limits are designed as 5,334,000 gas. Thus, the minimum transaction numbers are 254 (5,334,000/21,000). To calculate the throughput of blockchain explorers, we could use the minimum transaction numbers to divide the relevant latencies. Therefore, the throughput evaluation result is presented in Table 4, in which 'tps' refers to transaction per second. It is found that the throughputs/tps of blockchain explorers are 22.52, 17.22, 37.35, 38.72, which are much considerable than the Ethereum public network (15 tps). It means that imseStudio is practical to adopt in service manufacturing industry.

$$\min \ \textit{Transaction numbers} = \frac{\textit{Block gas limit}}{\textit{Transaction gas limit}} \tag{7}$$

5.4. *Discussion and limitation*

From the experimental case study, key findings and results are summarised, which are useful for various manufacturers to make service decisions under a blockchain-enabled secure digital twin platform. Firstly, SOA-oriented architecture is designed and developed through four blockchain explorers, including printer explorer, customer explorer, matcher explorer and executer explorer. Different users (e.g. customers and printers) could access the relevant explorer easily through the

Table 4. The performance evaluation results of imseStudio.

Criteria	Operation	Blockchain explorers: Printer explorer	Customer explorer	Matcher explorer	Executer explorer
Latency/s	Publish	11.28	14.75	6.80	6.56
	Retrieve	5	5	Nearly real-time	Nearly real-time
Throughput/tps	Publish	22.52	17.22	37.35	38.72
	Retrieve	50.80	50.80	N/A	N/A

Table 5. Comparison of the imseStudio with the existing works.

Author (year)	Scope	Aim (s)	Approach	Platform implementation
Tao et al. (2020)	Manufacturing service collaboration	(1) To facilitate the manufacturing service collaboration	The collaboration mechanism designed by integrating blockchain and digital twin	Conceptual level
Li et al. (2021)	Resource sharing in social manufacturing	(1) To enable software copyright protection (2) To simplify heterogeneous manufacturing resource integration	A Hyperledger blockchain-based digital twin sharing platform	Implemented level
Lee et al. (2021)	Information sharing in construction	(1) To enable an accountable information sharing	An integrated framework of digital twin and blockchain	Ongoing level
Huang et al. (2020)	Data management of product lifecycle	(1) To enable data storage, access, sharing and authenticity in the product lifecycle	A data management method for product digital twin using blockchain	Conceptual level
The proposed imseStudio	Manufacturing resource servitisation	(1) To servitise the manufacturing resources in a trustable manufacturing environment	An Ethereum blockchain-enabled secure digital twin platform using SOA architecture	Implemented level

open web service. For example, the 3D printing manufacturer of SMEs could use the printer explorer to servitise the manufacturing resources and provide digitalised services to the target customers. Thus, not only could imseStudio help the SMEs improve the digitalisation capacity, but also help the SMEs save the cost to implement and maintain the digital solutions. Secondly, the effectiveness and efficiency of imseStudio are demonstrated through two aspects: the application of four blockchain explorers and the performance evaluation. For example, the application of four blockchain explorers facilitates the order placement and traceability services by an easy-to-use web service to timely acquire the printing progress. Moreover, the quantitative performance analysis proves that imseStudio could effectively work with considerable efficiency in a real-life case. Finally, blockchain provides a secure environment for the customers and manufacturers. In the blockchain-enabled environment, the digital twins of customer orders and manufacturing resources could be securely created, configured, matched and executed. Thus, trust and collaboration could be facilitated amongst the customers and manufacturers.

Table 5 shows the comparisons between the proposed imseStudio with the existing works to demonstrate the advantages for servitising the manufacturing resources. Three observations could be made as follows. Firstly, many existing works are still at the conceptual level. The implementation of imseStudio could be a pioneer to explore the application of blockchain and digital twin in industry. Secondly, most digital twins are made using software (e.g. solidworks, CAD, etc.). In contrast, imseStudio uses the JSON-based format for making digital twin of manufacturing resources, which provides an alternative to servitise the manufacturing resource. Thirdly, imseStudio is implemented based on the Ethereum blockchain. Compared with Hyperledger Fabric, Ethereum enables a public network with a flexible registry and join, which conforms with features of service manufacturing (e.g. open and sharing).

The limitations are presented in three aspects. Firstly, this paper mainly considers the servitisation of 3D printers. The other manufacturing resources, such as laser-engraver, grinder, etc., are not yet included using the JSON-based data format. It provides an open opportunity to explore more service manufacturing scenarios. Secondly, the interoperation between physical twin and digital twin is not discussed in detail. Cyber-physical interoperation is vital to achieve smart manufacturing floors. More smart sensing technologies could be applied to facilitate the real-time perception and feedback. Finally, this paper focuses on the effectiveness and efficiency of imseStudio. The quantitative analysis, such as optimised printing time, printing schedule, is not discussed to accurately identify the advantages of imseStudio.

6. Conclusion and future research

To facilitate the service-oriented transformation in SMEs, this paper introduces a blockchain-enabled secure digital twin platform. Firstly, the architecture of blockchain-enabled digital twin platform for service manufacturing is proposed and developed, named imseStudio. It provides a secure and trustable environment for digital twins through the blockchain's immutability and reliability. Secondly, the service-oriented digital twinning model is built to transform diverse manufacturing resources into digital twins, which are securely stored in the blockchain ledger. Finally, an experimental case of 3D printing service is given to verify the feasibility of the imseStudio.

This paper's main contributions can be summarised as follows: (1) this paper contributes a blockchain-enabled secure digital twin platform in service manufacturing. Through the service-oriented digital twin model, the digital twins of manufacturing resources could be created, interoperated and matched in the blockchain environment. Not only does it servitise manufacturing resources into digital twins, but also provides an effective solution to promote the transformation towards service manufacturing. (2) The rule-based off-chain matching mechanism is developed to achieve the flexible matching service in 3D printing services. Two sets of matching rules include the basic matching rule (e.g. size, material, accuracy) and the advanced scheduling rule (e.g. order priority, customer importance). These rules are deployed at the off-chain side, which provides the backbone to the matcher explorer. (3) Four blockchain explorers are innovated to enable 3D printing services, including order placement, asset digitalisation, matching and scheduling and execution and monitoring. Through the experimental case study, customer explorer provides a straightforward approach to placing orders and tracking printing statuses. Printer explorer facilitates the printing servicers to servitise their manufacturing resources. Matcher explorer plays a role as a matchmaker to schedule customer orders to suitable printers. Executer explorer provides a solution for the frontline operators to streamline the printing operations and helps the managers supervise the real-time printing activities and make production decisions flexibly.

Further research could be conducted in the following aspects. Firstly, collaborative service manufacturing could be considered using the developed imseStudio platform. For example, imseStudio could servitise multiple service manufacturing resources, such as grinding, laser-engraving, CNC, etc. It is worthwhile to explore the blockchain-enabled collaborative mechanism amongst different manufacturers to fulfil customer demands. Secondly, the implementation of a smart contract-enabled matching mechanism needs to be explored, such as development, deployment and versioning mechanism, etc. It could facilitate a practical and flexible matching solution for the manufacturing industry. Thirdly, the current platform is only implemented and verified in the 3D printing service scenario. It could be extended in other service manufacturing scenarios, such as mold manufacturing, assembling, etc.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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