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Blockchain-Based Fine-Grained Digital Twin Sharing Framework for Social Manufacturing

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ABSTRACT

The lack of digitalization basis of social manufacturing resources has brought barriers to perform efficient production coordination in social manufacturing network. Digital twin can be a promising carrier for bridging this gap. However, the complexity of digital twin makes small and medium enterprises, and individual resource owners in social manufacturing hard to apply this technology. Benefiting from the convenience of sharing in social communities, this paper presents a blockchain-based fine-grained digital twin sharing framework to accelerate the popularization and iteration of digital twins in social manufacturing. A hybrid design method, called model–view–controller domain-driven design (MVC-DDD), is proposed to decompose and decouple complicated digital twin instances into small granules from software architecture perspective. Then, blockchain is introduced as the underlying infrastructure to innovate the specific sharing mechanisms using zero-knowledge proof for decentralized registering, authorizing, and extracting digital twin granules. Moreover, the sharing incentive mechanism is also explored to ensure the feasibility and sustainability for the whole sharing behaviors. Finally, different types of 3D printers are selected for implementing the referential digital twin architecture for generating the sharable granules. A series of experiments are conducted to show that our sharing mechanism has a good performance in terms of throughput, latency and network bandwidth. Additionally, the incentive mechanism is also analyzed generate the management implications to facilitate the digital twin providers with different scales for sharing.

Keywords: Social Manufacturing, Digital Twin, Blockchain Technology, Sharing Incentive Mechanism.

1. INTRODUCTION

Social manufacturing has brough a new revolution to the manufacturing industry upon cloud manufacturing. It reconstructs the organization of manufacturing resources in a flatter management structure, to further enhances the flexibility and agility to satisfy the personalized and customized production demands extracted from the social network in a cloud service manner [1]. Besides, social manufacturing has also encouraged the engagement of idle manufacturing resources that are separated and not originally specialized for profitable production, such as 3D printers in universities [2]. In such a condition, production demands may be released to manufacturing resources that belong to different owners. Thus, social manufacturing must depend more on the efficient coordination among manufacturing resources to deliver satisfactory production services [3]. The concept of cyber physical social system (CPSS) is then emerged as the enabling technology to realize the multi-dimensional coordination [4]. Digital twin has been recognized as the most promising pillar of CPSS to establish the interoperability between manufacturing resources and social manufacturing network due to two reasons [5]. First, a digital twin can synchronize the real-time data from its corresponding manufacturing resource, which is key input for distributed production coordination since the resources are physical discrete in social manufacturing. Second, a digital twin can be virtualized and authorized to demanders to configure and operate manufacturing resources just as they own it, because some resource owners are not professional and sophisticated to operate these machines. Third, the simulation capacity of digital twins makes it possible to make collaboration optimization in cyber space rather than releasing the production demand using dispatching rules.

Since a digital twin involves the knowledge from multi-dimension, multi-spatial-temporal scale, multi-discipline and multi-physical quantities, the development of a digital twin is usually knowledge intensive and time consuming [6]. Leading manufacturers have profound technology accumulation to promote digitalization of their manufacturing resources into digital twins. While social manufacturing has also been flooded with small and medium manufacturers, and even individual households. The threshold of digital twin development makes them incapable of benefiting from the intelligent transformation brought by digital twins. Hence, the lack of digital twins in these subjects limits the implementation of CPSS in large-scale social manufacturing network, which weakens their competitiveness and results in polarization of social manufacturing market in terms of service intelligence and efficiency.

Benefiting from the sharing convenience of social manufacturing community, knowledge related to design and production has been widely and frequently shared and transferred in social manufacturing [7]. Moreover, the social collaboration also facilitates the generation of new knowledge. The management of knowledge sharing has become the key to protect the rights of knowledge stakeholders from social manufacturing communities and current issues have already aroused many interests from researchers. The related studies manifest into three directions. The first direction focuses on the macro mechanisms for the sharing behaviors. Specific mechanisms were designed to encourage, motivate, and prove the overall benefits of knowledge sharing [8,9]. The second direction aims at the service-oriented knowledge sharing that explores the transformation and encapsulation methods to represent the knowledge in the form of services [10]. Then, the third direction focuses on the knowledge sharing protection that shields the unauthorized accesses to the knowledge or its services [11].

However, the sharing of digital twins encounters more real-life challenges due to their complexities. First, a digital twin is an integrated entity of cross-domain knowledge [12]. For example, a generic digital twin for machine tools needs to at least merge the knowledge of geometry, mechanical features, data system and human-machine interaction. Current study has explored the sharing of a complete digital twin, while this means is detrimental to the reuse of its partial knowledge inside [13]. Second, the formation of a social manufacturing community depends on the common interests, capacity, and knowledge from a definite domain [14]. The cross-domain knowledge encapsulated in a digital twin is difficult for single community to understand, apply, maintain, migrate, and promote. Third, the sharing intention for digital twin owners is not so strong because some involving knowledge may be the trade secret or core competence and they are afraid that the sharing of a whole digital twin may leak these knowledge indirectly. To sum up, the root of the digital twin sharing problem lies in the coarse granularity of a digital twin. Hence, a fine-grained sharing for a digital twin is worth exploring, as a feasible solution. While it also accompanies some emerging issues, summarized as follows:

- How can a digital twin be built in a fine-grained manner with the consideration of separating internal representations of digital twin from its business logic disposal and domain knowledge encapsulation?
- How can fine-grained digital twins be shared in a distributed and decentralized social manufacturing network?
- How can the incentive mechanism be designed to motivate the sharing of digital twins through the established social manufacturing network?

To address the above questions, this paper presents a blockchain-based fine-grained digital twin sharing framework (BCFG-DTSF) to facilitate digital twin sharing in the social manufacturing network. A novel design approach is proposed to integrate the model–view–controller (MVC) design pattern with a domain-driven design concept to separate and encapsulate the knowledge from the business logic of digital twins. Then, blockchain technology is introduced to establish the decentralized sharing network, which provides the underlying basis to securely execute the management behaviors for digital twin granule registration, authorization, and instantiation. Finally, an incentive mechanism is designed to motivate the fine-grained sharing of digital twins.

The rest of this paper is arranged as follows. Section 2 reviews the related work. Section 3 illustrates the MVC-based domain-driven design method. Section 4 describes a reference ontology for fine-grained digital twins. Section 5 presents the blockchain-based sharing infrastructure. Section 6 designs and proves the incentive mechanism. Section 7 verifies and evaluates the proposed framework using a demonstrative case study. Section 8 presents a summary of this research and potential future work.

2. LITERATURE REVIEW

2.1. Social manufacturing

Social manufacturing is conceptualized as a new kind of networked manufacturing paradigms that supports the organization of socialized manufacturing resources to timely satisfy the growth of personalized demands on crowd intelligence for co-creating open architecture products. It has been established on the cloud manufacturing, open manufacturing and universal manufacturing, which digitalize, intelligentize and standardize the distributed manufacturing capacities into various kinds of manufacturing services to satisfy the diverse and complex production demands.

The social media has brough two driving forces. The first one facilitates the formation of personalized and customized production demands those are mined and released from the social interactions. Social media provides the channel and method to gather and coordinate the design and production demands. Since this is the initial driving force, it has accordingly drawn much attention. Aiming to facilitate the cross-enterprise manufacturing demand-capability matchmaking, [15] designed a deep learning model to extract the social manufacturing relationships among various named entities. [16] conducted a complexity analysis based on the social learning evolution method to explore the effect of social factors in the evolution process to maintain a sustainable development of social manufacturing. To tackle the social-cyber complexity, [17] proposed a computational experiment-based evaluation framework to simulate the adaptability of different service matching strategies for performance optimization. [18] designed a supervised learning approach to extracting relationships from social manufacturing network and provides a group-level relationship matching mechanism for social entities. To address the large-scale group decision making issue brought by the social media driven manufacturing collaboration, [19] presented a social network community detection approach based on the fuzzy clustering method for social manufacturing network generation. Aiming to enhance the home cognition in consensus agreement on social media, [20] proposed an eight non-linear time variant models for opinion dynamics and revealed its implications for social manufacturing.

Another driving force from social media promotes the clustering of manufacturing resources into social communities, especially for the idle and distributed resources from small and medium enterprises. Recent research can be further categorized into three concerned aspects. First, the formation of social community for manufacturing resources is widely explored. [21] proposed a blockchain-driven model to handle the cyber-credit of a social community for makers, which facilitate the self-organizing process of social manufacturing for co-creating open architecture products. [4] presented a contextual self-organizing model for manufacturing resources based on the Social Internet of Things strategy to boost sociality and narrow down the contextual computing complexity based on situational awareness in a cyber-physical-social connected space. [22] explored the evolution of self-organizing social manufacturing network from the view of evolutionary dynamics with the considerations of homophily and heterophily.

Second, the collaboration of social manufacturing resources inside or outside community is also discussed. To realize the design and production collaboration, [23] designed a collaborative framework using the social media with a live streaming process. [7] highlighted the importance of the social aspect in social manufacturing and illustrating the diverse types of value created through alternative fashion collaborated design strategies. .[24] presented a flexible collaborative network model with Louvain algorithm to extract suitable manufacturing communities from the social manufacturing network. [25] developed a digital twin collaboration platform using blockchain technology to address the distributed and decentralized collaboration execution with socialized manufacturing resources.

Third, the sharing convenience of social community for experiments and knowledge attracts much attention. [2] proposed the concept of shared factory as an independent socialization manufacturing mode and revealed the benefit in contributing to the integration of the manufacturing and service sectors. [13] designed a digital twin sharing platform to facilitate the heterogeneous production resource integration in social manufacturing. [26] developed a secured big digital twin data sharing system based on blockchain to enhance the circulation of exponentially growing and timely data among stakeholders.

In general, digital twin technology has been regarded as the key enabling technology to realize the collaboration in social manufacturing. To promote the popularization of digital twin application, current study has made preliminary exploration to sharing the whole digital twin object with the benefit from the sharing ease in social community. However, a digital twin is usually a complicated object with cross-domain components. Considering the enthusiasm of innovation in social community, it seems that a more fine-grained digital twin sharing schema is worth discussing to make more digital twins.

2.2. Digital twin modeling

The concept of a digital twin originated from the information mirroring model proposed by [27]. It has been formally defined as an integrated multiphysics, multiscale, probabilistic simulation of an as-built system that uses the best available physical models, sensor updates, behavior history, etc., to mirror the life of its corresponding flying twin [28].

Since digital twin modeling is recognized as the theoretical foundation of digital twin applications [29], it has attracted considerable attention from academia and industry. Preliminary digital twin models are usually built from the cyber-physical perspective. For example, [30] proposed a three-dimensional digital twin model to establish digital mapping in virtual space using connections with physical space for real-time data collection. Then, [31] enriched this model with two additional dimensions, data, and service, to strengthen the data-driven and service-oriented features of a digital twin. Based on this model, [32] designed a model utilizing the theory of inventive problem solving (TRIZ) as a function to represent the complex relationship between digital twin objects and their attributes. [33] presented an elaborated digital twin reference model to identify various degrees of basic and hybrid computation-interaction modes during digital twin system implementation. To facilitate the generic construction of digital twins, [34] introduced a cyber-physical system (CPS)-based architecture for manufacturing digital twin establishment with a novel trimodel-based approach.

More focus has been dedicated to the data perspectives of digital twin. [35] designed a three-layered digital twin model considering the data flow from real-time data transmission and processing to mining to systematize the development methodology for digital twin. [36] highlighted the significance of semantic digital twin and depicted a semantic framework for construction applications to promote the ability of digital twin in business-related data expression. To separate heterogeneous semantics, [37] proposed another five-dimensional digital twin in terms of geometry, physics, behavior, rules, and data to make more accurate digital twins for a physical shop floor. To facilitate the development of high-fidelity multiscale and multidimensional digital twins, [38] presented a digital twin mimic model based on biomimicry principles that can adaptively construct a multiphysics digital twin of the machining process. To realize the digital semantization of complex manufacturing systems, [39] developed a resource virtualization method to build the digital twin of a smart factory. For semantic modeling language, current studies usually take Modelica for multiphysics modeling and semantic web languages and Web Ontology Language (OWL) and Jena for virtual or digital entity modeling [6].

In general, current digital twin models still depend on cyber-physical and data/process logic-based modeling methods. Since the working digital twin is also a software system, formulating digital twin from the software architecture perspective appears to be long neglected.

2.3. Blockchain-based sharing solutions

Blockchain is a novel decentralized infrastructure and distributed computing paradigm that takes a chained data structure for verification and storage and uses distributed consensus algorithms to generate and update data [40]. Blockchain adapts cryptology methods to protect data transmission and access and applies automated script-based smart contracts to operate rules and data processes [41]. Blockchain was proposed by [42] as a decentralized ledger widely used in initial coin offerings, e.g., Bitcoin.

These technical features of blockchain stimulate and migrate its application for trust-free scenarios with multiple stakeholders, especially data sharing [43]. Privacy issues have attracted much attention, especially in medical field. [44] proposed a blockchain-based medical data management scheme to realize privacy-preserving sharing by the combination of access control protocol and symmetric cryptography. [45] has presented a blockchain based searchable encryption scheme to ensure the integrity, anti-tampering, and full traceability for shared medical data. To shield identity privacy, [46] developed a consortium blockchain with a universal anonymous sharing model and designed an improved consensus algorithm to optimize blockchain performance. Data trustworthiness and authentication is another concern in data sharing. To avoid over-reliance on the trusted agencies, [47] designed a blockchain-based security authentication scheme for medical data sharing. [48] proposed a blockchain-based data authentication system with edge computing to construct a distributed and trusted environment for collaborative data sharing. To realize cross-domain authentication, [49] introduced multiple signatures based on threshold sharing to build an identity federation in blockchain environment so that cross-domain communication can be reliable by smart contract.

On this basis, researchers have extended the sharing scope to more kinds of digital assets. To enable a secure and trustful environment for mold design knowledge licensing and transfer, [50] proposed a blockchain-based knowledge-sharing platform integrated with a private cloud to record mold design knowledge. Focusing on knowledge sharing in the edge computing environment, [51] designed a novel user-centric blockchain to preserve edge knowledge sharing among decentralized intelligent network edges. [52] also presented a permission edge blockchain to manage peer-to-peer energy data and a knowledge-sharing process for their novel energy-knowledge-trading incentive mechanism. Concerning digital twin sharing, current study focuses more on the data sharing among digital twins. [53] analyze theoretically and practically the building of a digital twin for additive manufacturing in the aircraft industry through the exploitation of Blockchain and suggested that a blockchain-based information-sharing method is a potential solution ensuring information security among digital twins. [54] designed a EtherTwin system that integrates a blockchain-based owner-centric decentralized model for secure information management of Industry 4.0 assets. [26] optimized the use of blockchain only to record the hash value and transactions of digital twin big data to reduce the storage cost of blockchain nodes. [55] introduced blockchain for data authentication and accounting of digital twins and established a blockchain-based information sharing framework for stakeholders in construction projects. Besides data sharing among digital twins, blockchain is also involved to make instance sharing of digital twin. [56] proposed a novel manufacturing blockchain of things architecture for the configuration of a secure, traceable, and decentralized digital twin manufacturing cell. [13] has developed a blockchain-based sharing platform for sharing digital twin entities among social communities. However, the coarse-grained knowledge sharing is hard for recombination and reconfiguration, especially for a fully encapsulated digital twin, which impedes creativity from social communities. With breaking down digital twins for sharing in social manufacturing, it is worth exploring the specific mechanisms for managing these digital twin granules considering privacy-preserving copyright protection and storage policy using blockchain.

2.4. Summary and research gaps

Through the literature review from the above three aspects, the research gaps are analyzed and summarized as follows.

From the problem background domain, the trend of social manufacturing has manifested into two sides. One is the demand side that the social media extremely drives the release of customized and individualized production. Due to the aggregation effect brough by social media, demanders can easily be gathered and work for the same interest. The co-design and co-development within the social community have become the root cause of generating differentiated production demand. Besides physical goods, a social community can also generate software products. The MIUI system from Xiaomi is derived from a BBS (Bulletin Board System), where at the very beginning, developers are virtually collected and contribute a variety of versions with different features for this operating system under the uniform Android architecture. Thus, social communities provide a sound organizational basis to conduct sharing behaviors and a well-recognized software architecture is essential for boosting the creative enthusiasm. The other side is the resource domain that digital twin has been proven to be a feasible solution for digitalizing social manufacturing resources for flexible organization and efficient coordination. However, the complexity of digital twin makes small and medium enterprises, and individual resource owners in social manufacturing communities hard to apply this technology. Thus, from the problem domain, we need to develop the sharing advantages of social communities to decompose the complexity of digital twins and contribute every small parts of digital twins. Moreover, we also need to think about how to enhance the sharing willingness of leading companies in the field of digital twins to public and license their digital twins.

From the digital twin modeling aspect, current digital twin models have given clear ontological descriptions for the definition, constituent structure, and fundamental functionalities. These constitute the theoretical basis to generate the same understanding of digital twins. As a kind of digital replica, digital twins are commonly represented in the form of software system. However, it is difficulty for developers to have a full recognition of a digital twin in terms of its interdisciplinary models included. Thus, the separation of complexity of digital twins from software model perspective is critical for promoting reusability, scalability, and maintainability of digital twin systems. Meanwhile, to encapsulate each complexity in a small granularity facilitate the high cohesion and low coupling of digital twin systems, which is apt for knowledge sharing and re-assembling. It seems existing digital twin models have paid less attention from software architecture perspective and too abstracted to be instantiated into a referential architecture for development and encapsulation of digital twins for sharing purpose. Hence, there should be a design methodology to break down the complexity of digital twins and refining them in a fine-grained manner so that the elements of digital twins can be easily shared and reused in social communities. Then, a referential digital twin architecture should be explored, not only to guide developer communities to generate more structured building blocks of digital twins, but also to facilitate the circulation of inclusive digital twin knowledge for establishing an ecosystem for digital twin development, sharing and maintenance.

From the blockchain-based knowledge sharing perspective, current adoptions of blockchain technology have remained in a preliminary stage, which just integrate the blockchain as a kind of general database that can be decentralized accessed among multiparty for data sharing. Since knowledge sharing associates more about knowledge right certification, contribution incentive and transfer protection among multiple stakeholders, more exploration on blockchain should be conducted on a basis of previous data sharing, to take advantages of transparency, immutability, and traceability of blockchain to realize the process control for the whole digital twin sharing.

In summary, the weak-centralized social communities in social manufacturing have offered a sound sharing convenience to conduct digital twin sharing for leveraging the digitalization of social manufacturing resources. Thus, how to construct the sharing infrastructure, how to make digital twins sharable in a small granularity, how to share and incentive sharing behaviors are the key research gaps to be bridged in this research.

3. FINE-GRAINED DESIGN OF DIGITAL TWINS

3.1. MVC-DDD approach

The common five-dimension digital twin architecture provides an abstraction of digital twins from the macro composition and structure perspectives [57]. To enrich this model from the view of software engineering, this paper proposes an MVD-DDD approach as a scientific guidance for the development and implementation of digital twin systems. Since each model of the above digital twin architecture will associate cross-domain knowledge, which increases the difficulty to develop and implement models from a single domain. For example, the connection model between physical entity and virtual entity may contains a plenty of techniques in the fields of communication, industrial control, and sensor. Thus, the separation of different knowledge domains is essential for practicing the initiatives of making more digital twins [58]. Moreover, the reusability of each knowledge domain is also critical to ease the development burden of building digital twins, especially when all the knowledge domains are well encapsulated by software instances/components. In such conditions, the MVC-based domain-driven design (MVC-DDD) approach is newly introduced as a combination of MVC design architecture [59] and the concept of domain-driven design [60]. According to the concept of domain-driven design, a digital twin could be partitioned into several domains, and a domain can also be extended by the bounded context to restrain the boundaries of its inner business logic. Thus, we present definition 1 and definition 2:

Definition 1. *A digital twin can be formally defined by DDD as a nonempty set of domains,* $DT^{DDD} = \{D_1, D_{2,\dots} D_l\},\ l \in N^*$

Definition 2. *A domain can be expanded by a nonempty set of bounded contexts,* $D = \{bc_1, bc_2, \dots, bc_m\}, m \in N^*$

MVC aims to decouple the user interface (view), data (model), and business logic (controller) for software entity separations. Among them, the view renders the presentation of the model in a user-interactive format. The model is invoked by the controller to handle the data. The controller receives and processes user interactions in terms of application logic. Hence, on the basis of MVC, we also have definition 3 to define a digital twin:

Definition 3*. A digital twin can be formally defined by MVC as a triple* $DT^{MVC} = \{M, V, C\}$*, where.*

- M *is the nonempty set of models of a digital twin,* $M = \{m_1, m_{2,\dots} m_i\},\ i \in N^*$.
- V *is the nonempty set of views of a digital twin,* $V = \{v_1, v_{2,\dots} v_j\},\ j \in N^*$.
- C *is the nonempty set of controllers of a digital twin,* $C = \{c_1, c_{2,\dots} c_k\},\ k \in N^*$.

Since MVC focuses on the separation of application logic, it neglects the encapsulation of business processes, which makes it too fragmented to be shared. For example, even though a single view element is prone to be reused for development, it cannot be directly integrated or easily migrated to another digital twin as encapsulated knowledge. Hence, the concept of a domain is introduced to enhance the cohesion of MVC elements to realize domain knowledge encapsulation. The MVC-DDD approach is formulized in definition 4.

Definition 4. *The elements in* DT^{MVC} *can be encapsulated in bounded contexts; then,* $\exists\, M' \subseteq M$, $V' \subseteq V$, $C' \subseteq C$, *and* $bc_m \in D$ *subject to:*

$$bc_m = (M' \cup V' \cup C')$$

$$M' \neq \emptyset$$

$$V' \neq \emptyset$$

$$C' \neq \emptyset$$

Meanwhile, $\forall bc_i, bc_j \in D$, $\forall D_i, D_j \in DT^{DDD}$, *subject to:*

$$bc_i \cap bc_j = \emptyset$$

$$D_i \cap D_j = \emptyset.$$

$$DT^{MVC} = DT^{DDD}$$

According to the above definition, a digital twin can be partitioned from two dimensions. The prioritized dimension is domain driven design to separate the complexity from the interdisciplinarity and cross-domain of digital twins according to *Definition 1*. Then, breaking down each domain into bounded contexts decouples the functionalities within a domain based on *Definition 2*. Afterwards is dividing a digital twin into MVC elements considering separating operation logics as shown in *Definition 3*. Finally, we should assign MVC elements into different bounded contexts for granule encapsulation.

3.2. Fine-grained digital twin architecture based on MVC-DDD

According to the definitions of MVC-DDD, a referential digital twin architecture is built in Fig. 1. First, the application domain of a digital twin should be extracted from its behavioral responsibility. In social manufacturing, the behavioral responsibility of a digital twin could be partitioned into three domains. The ontology domain gives physically existing descriptions of digital twins so that they can be identified and discovered objectively in the social manufacturing network. The enabling domain separates the advanced abilities that aim to enhance digital twins' physical performance. It also acts as middleware to shield the functional heterogeneities of a digital twin in terms of communication, sensing, and control in case of their influences on other domains and vice versa. The business domain focuses on the disposal of application logic to make digital twins capable of satisfying social manufacturing demands.

Second, each domain is further divided into one or more bounded contexts to promote the division of inner responsibilities. The ontology domain consists of physical context, mechanical context, and formalization context. The enabling domain can also be divided into communication context, sensing context, and automation context. The business domain focuses on processing three key business behaviors: task, simulation, and service.

Third, from the development view of digital twin, a digital twin can be constructed by a series of MVC elements. The model component separates all the data-related logic from the bounded context. It responds to the requests from the views and manipulates the data that are being transferred between controller components without any application logic. The view component represents all the user interface logic of each context. It extracts and visualizes the data from the model components and is driven by the controller components for content update. The controller realizes the encapsulation of context business logic and acts as the connector between model and view

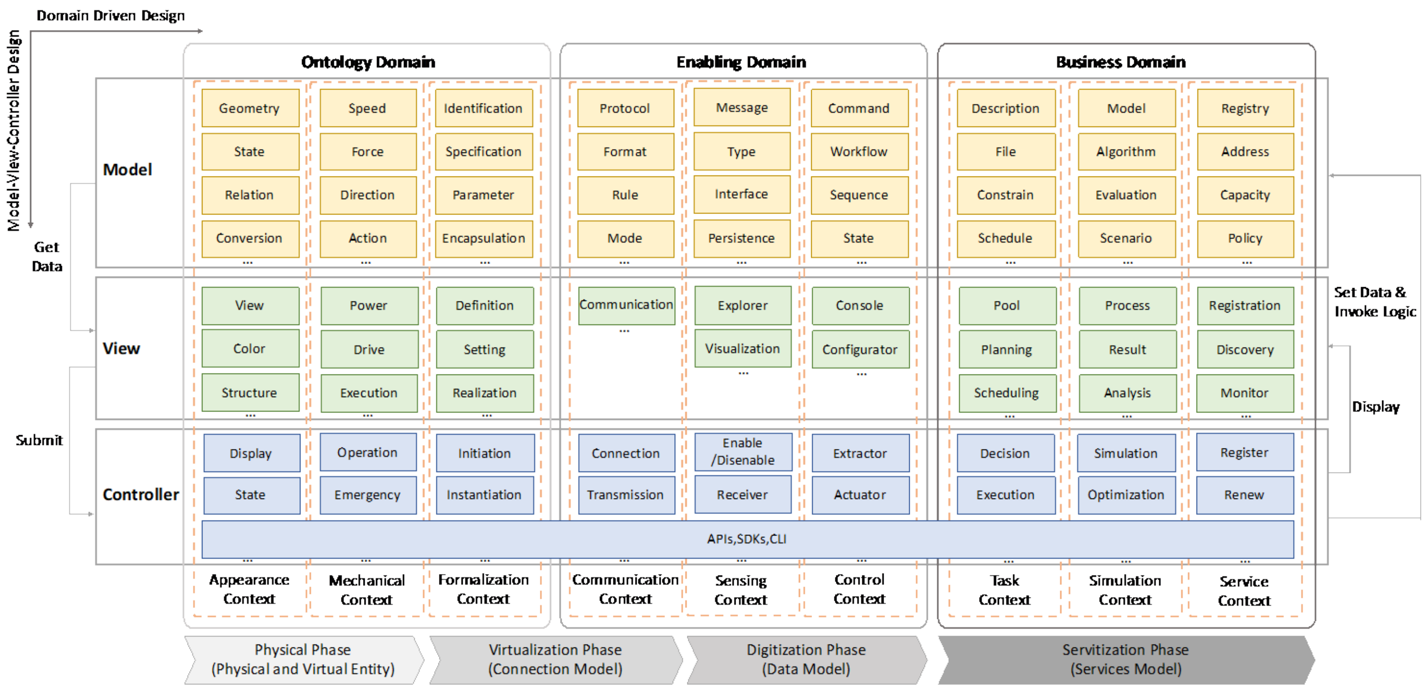


Fig. 1. Referential digital twin model using MVC-DDD

components. Generally, it processes the received requests, invokes the model components for data disposal, and associates with view components for user interactions.

Finally, the MVC elements are encapsulated in a bounded context, and each bounded context is converted into a microservice. These microservices are further categorized into four lifecycle phases. The physical phase achieves physics-based modeling according to the parameters, performance, and specifications of the physical entity of a digital twin. The virtualization phase completes the transformation from physical space to cyber space to realize bidirectional interoperability. The digitalization phase enriches the real-time descriptions of digital twin through the sensing contexts so that a more accurate digital twin model can be formulized to react to controlling the physical entity via the automation context. The servitization phase converts the business functions in the form of services to construct a service-oriented digital twin for social manufacturing task management and simulation.

4. BLOCKCHAIN-BASED DIGITAL TWIN SHARING

4.1. Design of sharing framework

The BCFG-DTSF follows a four-layer architecture, as shown in Fig. 2. The bottom layer is infrastructure-as-a-service (IaaS), which provides general store services for digital twin sharing. The Interplanetary File System (IPFS) is a distributed file system that realizes the storage and distribution of digital twin context pieces. The adoption of file sharding makes it more secure to avoid the leak of digital twin context from a single repository. In addition, the piece redundancy policy can easily be applied to improve the storage availability, avoiding single-point failure. The consortium blockchain system is a nonrelational database that stores a variety of transactions. Since the nature of social communities is a kind of consortium, we select consortium blockchain because it is apt for organizing community members and has better performance in terms of data sharing and privacy protection [61]. The fundamental role of blockchain manifests into three aspects. First, it works as the storage mechanism of the sharing framework and achieves the tamper-proofing feature. Since we have separated the storage of raw digital twin granules at IPFS, blockchain is mainly adopted for persisting proofs generated by digital twin sharing. Second, blockchain provides a transparent and creditable environment to execute smart contracts for verifying proofs. Smart contracts can be audited and deployed at blockchain to ensure their execution security to prevent the malicious attacks on proof falsification and crack. Third, the consortium blockchain provides underlying mechanisms for weak-centralized organization of consortiums, which are essential to be invoked by upper services. For example, the identity service in the SaaS layer depends on the organization structure to issue group signatures within a social community.

The Platform-as-a-Service (PaaS) layer consists of four core services for platform use. The node management service is responsible for constructing and maintaining the peer-to-peer network so that both IPFS nodes and blockchain nodes can be enrolled in the social manufacturing network and seamlessly connected. The transaction management service aims to define, configure and execute the transaction settings to guarantee appropriate processing for transactions. The chain management service is used to maintain the lifecycle of a blockchain. The message transportation service provides asynchronous service-to-service communication by receiving, storing, processing, and deleting messages based on the form of a queue so that the produced messages can be consumed by the correct receivers.

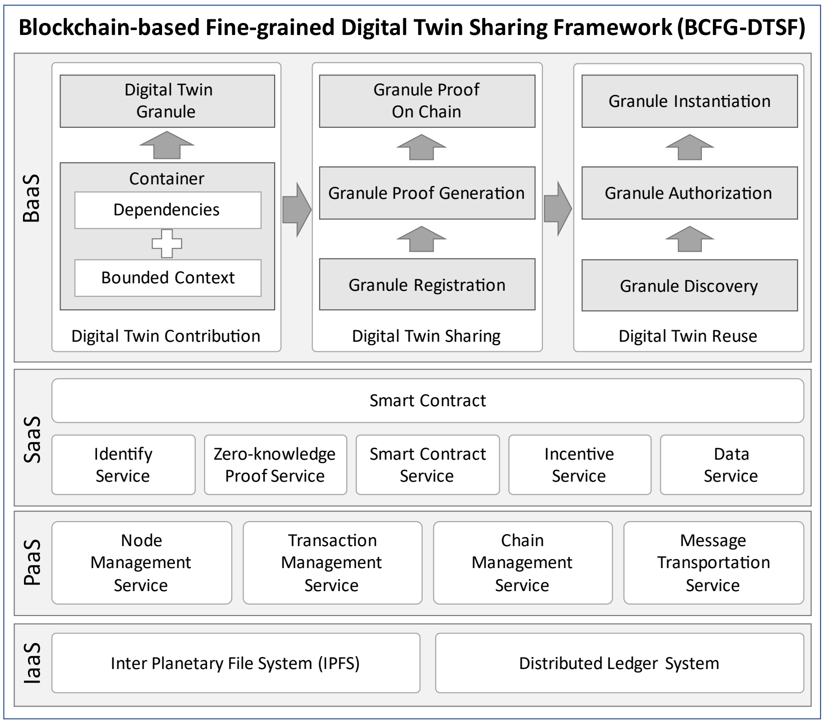


Fig. 2. Blockchain-based fine-grained digital twin sharing framework (BCFG-DTSF)

The Software-as-a-Service (SaaS) layer extracts the commonly used applications that are required to enable business logic processing in Blockchain as a Service (BaaS) and is dependent on PaaS. It includes five main services and one service-oriented functional component. The identity service provides a distributed multicenter identity registration, recognition, and management solution. It realizes trusted mapping between the real-life identity and on-chain identity of entity objects (e.g., human, machine, material), as well as the secure access authorization and data exchange between these entity objects. The zero-knowledge proof (ZKP) service enables a set of encryption schemes whereby one party can prove the truth of specific information to another party without disclosing any additional information. Smart contract services achieve lifecycle management for smart contracts through initiation, configuration, implementation, deployment, and destruction. The generated smart contracts are stored in the smart contract repository. The incentive service realizes the service-oriented encapsulation of the incentive mechanism to motivate participation in sharing digital twins. It is associated with smart contract services and consensus services for reward measurement, disposal, and release. The consensus service provides the underlying principles of data unit verification to achieve the necessary agreement on a single data value or a single state of the network among distributed ledgers and IPFS.

The BaaS layer abstracts and implements the business logic for the whole sharing process. The whole sharing consists of three phases. The first phase is the contribution of digital twins. Since the digital twin is constructed using the MVC-DDD method, a bounded context can be taken as the smallest granule. A container is adopted as the encapsulation to load both the bounded context and its dependencies. The second phase is to share the encapsulated digital twin granules among social manufacturing networks. The granule should initially be registered on the platform. Then, a granule proof is issued to prove the ownership of the registered granule. Finally, the proof is further stored on the chain so that the tamper-proof feature of the blockchain can guarantee its effectiveness and verifiability. The third phase is to reuse the shared granule for integration or implementation. The registered granule can be discovered by the intended community members. The registration information and proof of a granule can be disclosed for discovery reference. Then, the authorization is made using the zero-knowledge proof service to generate the proof, which is used to prove the legal acquisition of a digital twin granule by a definite member. Finally, taking a proof, the member can obtain the rebuilt granule that can be deployed directly in the target running environment.

Table 1. Notations

Symbol	Description
S	A digital twin granule sharer
$h()$	A hash function (i.e., SHA256)
A	A social manufacturing administrator
Pk_S^A, Sk_S^A	The group-use public key and private key generated by A for S
$zkp_g(i_1, i_2, i_3)$	A ZKP function to generate the proof. i_1 is the public inputs, i_2 is the private inputs, and i_3 is the constraints to be verified.
zkp_v	A ZKP function to verify the proof
Pk_S ,Sk_S	The public key and private key for S, where: $Pk_A = h(Sk_A)$
$st(msg, a, b)$	A way to safely transmit message from a to b
σ	A random salt
α	The unique non-substitutable ID of digital twin granule by S for registration
F	Source file of a digital twin granule
R_*	An operation record on a distributed ledger
P_*	A proof generated by the ZKP service
$Addr_*$	The block address of a record
$Addr_{*.brother}$	The brother nodes of the corresponding address
P_*	A root of a Merkle tree for a record
U	An intended user for obtaining shared digital twin granules
$c(Addr_{*.brother}, R_*)$	A calculation function for producing the Merkle root
n_i	The total amount of digital twins owned by a digital twin provider (DTP) i
m_i	The total amount of digital twins that a DTP i shares to the BCFG-DTSF
$V(m, n)$	The value generated from the digital twins when a DTP shares m amount of digital twins from its total amount n
$B(n_i)$	A calculation function to generate the intrinsic utility of a DTP i with n amount of digital twins
$C(m_i)$	A calculation function to generate the disutility of time and effort of a DTP i that shared m amount of digital twins to the BCFG-DTSF
E_i	The compensation for a DTP i based on the incentive mechanism
Z	The net utility of a DTP
π	The net payoff of BCFG-DTSF

* The symbol may have the following subscripts:
(i) α means it is related to the registration of digital twin granule α
(ii) $\alpha.U$ means it is related to the authorization of digital twin granule α to U
(iii) $\alpha.U.I$ means it is related to the instantiation of authorized digital twin granule α for U

4.2. ZKP-enabled sharing mechanisms

To realize the decentralized management of digital twin granule in social manufacturing network, six key mechanisms are designed to enable the granule registration, authorization, and instantiation through ZKP. The notations are given in Table 1 to describe each specific mechanism. The mechanisms will be encapsulated in smart contracts so that they can be deployed and executed on blockchain.

- Digital twin granule registration

An S can register its own digital twin granules by satisfying the following prerequisites. (1) S holds the Sk_S ;(2) An F can only be registered once. Then, the registration request from S can be conducted using *Mechanism 1*. Afterwards, S invokes a smart contract with P_α for blockchain disposal. The blockchain nodes then execute *Mechanism 2* to verify and endorse the received smart contract. If passed, R_α will be recorded in the distributed ledger and F_α will be persisted to the IPFS. Finally, $Addr_\alpha$ will be sent back to S.

Mechanism 1: Registration request

Input: $F_\alpha, Pk_S, Sk_S, \sigma$
Output: P_α
Set $\alpha \leftarrow h(F_\alpha)$;
Set $R_\alpha \leftarrow h(\alpha|Pk_S|\sigma)$;
Set *verifications*: $Pk_S \equiv h(F_\alpha)$ && $R_\alpha \equiv h(\alpha|Pk_S|\sigma)$;
Set $P_\alpha \leftarrow zkp_g([Pk_S, R_\alpha, \alpha], [Sk_S, \sigma], verfications)$;
Return P_α

Mechanism 2: Registration processing

Input: $P_\alpha, h(F_\alpha)$
Output: the processing result: *flag*
set *flag* $\leftarrow False$;
set α from P_α
if $\alpha \equiv h(F_\alpha)$ && $zkp_v(P_\alpha)$&& $a\ not\ in\ the\ registration\ record$, **then**
{ set *flag* $\leftarrow True$; }
return *flag*

- Digital twin granule authorization

An S can authorize its own digital twin granules to any third party by satisfying the following prerequisites. (1) Only a registered α can be authorized. (ii) S has the Sk_S corresponding to α. Then, the authorization proof $P_{\alpha.U}$ from S to U can be generated using *Mechanism 3* and smart contract will be invoked with $P_{\alpha.U}$ to request recording for this authorization. The blockchain nodes then execute *Mechanism 4* to verify and endorse the received smart contract. If passed, $R_{\alpha.U}$ will be recorded in the distributed ledger and $Addr_{\alpha.U}$ will be sent back to S. Finally, S should send $Addr_{\alpha.U}$ to U for next

Mechanism 3: Authorization request

Input: $\alpha, Pk_S, Pk_U, Sk_S, \sigma, \sigma', R_\alpha, Addr_{a.brother}, F_\alpha, M_\alpha$
Output: $P_{\alpha.U}$
set $R_{\alpha.U} \leftarrow h(\alpha|Pk_S|Pk_U|\sigma')$;
set *verifications*: {
$Pk_S \equiv h(Sk_S)$,
$R_\alpha \equiv h(\alpha|Pk_S|\sigma)$,
$M_\alpha \equiv c(Addr_{a.brother}, R_\alpha)$,
$R_{\alpha.U} \equiv h(\alpha|Pk_S|Pk_U|\sigma')\}$;
set $P_{\alpha.U} \leftarrow zkp_g([Pk_S, Pk_U, R_\alpha, M_\alpha, Addr_{a.brother}, \alpha], [Sk_S, \sigma', \sigma], verfications)$;
return $P_{\alpha.U}$

Mechanism 4: Authorization processing

Input: $P_{\alpha.U}, Addr_a$
Output: the processing result: *flag*
set *flag* ← $False$;
set α, M_α from $P_{\alpha.U}$;
if $zkp_v(P_{\alpha.U})$ & α is in the record & M_α is the root of $Addr_a$, **then**
{ set *flag* ← $True$; }
return *flag*

- Digital twin granule instantiation

After obtaining the authorization, *U* can get the digital twin granule by showing a proof of authorization to smart contract for instantiating this granule. This proof, $P_{\alpha.U.I}$, can be generated through *mechanism 5* and sent to smart contract to invoke IPFS. The blockchain nodes execute *mechanism 6* to verify and endorse this request. If passed, F_α will be packed with corresponding environment and return to *U* for instantiation.

Mechanism 5: Instantiation request

Input: $\alpha, Pk_S, Pk_U, Sk_U, \sigma', R_{\alpha.U}, Addr_{a.U.brother}, M_{\alpha.H}$
Output: $P_{\alpha.U.I}$
set *verifications*: {
$Pk_U \equiv h(Sk_U)$,
$M_{\alpha.H} \equiv c(Addr_{a.U.brother}, R_{\alpha.U})$,
$R_{\alpha.U} \equiv h(\alpha|Pk_S|Pk_U|\sigma')\}$;
set $P_{\alpha.U.I} \leftarrow zkp_g([Pk_S, Pk_U, R_{\alpha.U}, M_{\alpha.U}, Addr_{a.U.brother}, \alpha], [Sk_U, \sigma'], verfications)$;
return $P_{\alpha.U.I}$

Mechanism 6: Instantiation processing

Input: $P_{\alpha.U.I}, Addr_{\alpha.U}$
Output: F_{α}
set $M_{\alpha.U}$ from $P_{\alpha.U.I}$;
if $zkp_v(P_{\alpha.U})$ & $M_{\alpha.U}$ is the root of $Addr_{\alpha.U}$, **then**
return F_{α}

4.3. Digital twin sharing incentive mechanism

Since sharing behavior of digital twins is highly associated with stakeholders and digital twin granules, it is necessary to consider blockchain system when designing a sharing mechanism. Hence, technology is no longer the factor restricting digital twin sharing; rather, it brings more convenience to sharing. Currently, participants show interest in using the data made available through sharing platforms but refrain from sharing their own private digital twin granules. This behavior is attributed to the lack of incentives, as perceived by digital twin granules' contributors [62]. A large segment of the current literature uses the participation level or the amount of data uploaded by contributors to determine rewards [63,64]; thus, these platforms limit themselves to the quid pro quo of compensating other contributors. Such situations produce platform overcrowding with irrelevant and poor-quality data and deter active participation in sharing platforms [65]. Hence, the need for a reward mechanism that takes the specific attributes that drive the benefits and costs of individual contributors of digital twin granules into account has become imperative. In such conditions, we should measure the factors that drive the sharing behaviors of contributors and then reward/compensate participants with fair values throughout the blockchain.

The sharing incentive mechanism should consider the factors that drive the sharing behavior of the digital twin producers/owners (DTP). The sharing behavior depends on the attributes of the decentralized digital twin producers and their digital twin granules. For instance, producers experience a disutility from compromising their sensitive data or intellectual property leakage through digital twin sharing. Furthermore, complementarity among the digital twin granules of similar digital twins is also worth considering when developing an incentive mechanism.

In the following subsections, we model the sharing decision from DTPs. Each DTP decides their optimal level of digital twin sharing to the BCFG-DTSF. The BCFG-DTSF, in turn, generates value by serving the digital twin granules to any interested users that request to integrate these granules.

Consider x DTPs registered to the BCFG-DTSF. Here, DTPs aim to maximize their utility from digital twin sharing. In contrast, the BCFG-DTSF targets the increase in financial performance from the digital twins that aggregate over time, i.e., the BCFG-DTSF serves digital twins to potential users to generate revenue through creating more complicated digital twins. Additionally, we assume that each digital twin is unique to its DTP to eliminate the chances of redundancy in digital twin contribution from different DTPs.

4.3.1 Sharing framework's objective

Let $\boldsymbol{n} = (n_1, n_2 \ldots\ldots n_x)$, where n_i is the total amount of digital twins with DTP i. Now, let $\boldsymbol{m} = (m_1, m_2 \ldots\ldots m_x)$, where $m_i (\leq n_i)$ is the amount of digital twins that DTP i shares to the BCFG-DTSF. Consequently, BCFG-DTSF generates value from the digital twins given by $V(\boldsymbol{m}; \boldsymbol{n})$, which is the payoff or performance of BCFG-DTSF when the DTP shares m_i amount of digital twins from its total amount, n_i. Here, $V(\boldsymbol{m}; \boldsymbol{n})$ is increasing and concave in m_i to represent incremental performance improvement of BCFG-DTSF with the amount of shared digital twins.

Now, the DTPs differ in their productivity or potential impact on the performance of BCFG-DTSF due to the uniqueness of their digital twins. Hence, the marginal contribution of digital twins from DTP i to the performance of BCFG-DTSF is given by $\frac{\partial V(\boldsymbol{m};\boldsymbol{n})}{\partial m_i}$. Each DTP is unique in its contribution to the performance of BCFG-DTSF. For instance, a complete digital twin of a 3D printer that is readily available for printing may be of more value to the users, compared to a printer that is rarely available. Therefore, the BCFG-DTSF generates more value from serving digital twins of this kind of printers than the others. Additionally, we take into account the interdependence that may exist among the digital twins from different DTPs by the nature of the common functionality/purpose they serve, i.e., they all contribute to social manufacturing. Here, the digital twins could serve functionalities ranging from transportation, logistics, administration, etc., in the manufacturing environment. Hence, $\frac{\partial^2 V(\boldsymbol{m};\boldsymbol{n})}{\partial m_i \partial m_j} > 0$ accounts for a positive *interdependence* between the digital twins of DTP i and DTP j, representing the influence of the amount of digital twins shared m_j have on the change in performance induced by DTP i. Here, we omit the cases of negative interdependence for simplicity (but our results remain the same). In general, interdependence refers to the phenomenon where the digital twins are more valuable if more DTPs share it. Put another way, a DTP's willingness to participate in the BCFG-DTSF increases with the number of other participating DTPs. For instance, when more digital twin granules for 3D printers are shared at BCFG-DTSF, the users get to select/use the granules that are most ideal to serve their printing need based on factors, such as their printing costs, level of sophistication in printing or the availability of printers.

4.3.2 Cost of digital twin contributors

This study takes into account two contributing factors that impart costs to DTPs. First, DTPs experience an intrinsic utility, $B(n_i)$, from holding their digital twins private. Hence, DTP i experiences a decrease in utility given by $B(n_i) - B(n_i - m_i)$ when it shares m_i amount of digital twins. Here, $B(\cdot)$ is increasing and concave in m_i, i.e., $B'(m_i) > 0$ and $B''(m_i) < 0$. Therefore, when $n_i > n_j$, a DTP that holds n_i digital twins experience lower disutility from sharing a unit digital twin compared to a DTP with n_j digital twins. It is reasonable to assume that a DTP's private utility increases with the amount of digital twins it holds, i.e., $B'(m_i) > 0$. Similarly, when sharing an additional granules of digital twins, a DTP with a more considerable amount of digital twins experience a minor increase in utility compared to a DTP with a smaller amount of digital twins, i.e. $B''(m_i) < 0$. Therefore, the higher the level of digital twins sharing from the DTPs, the higher the drop in their utility.

Second, DTP i experiences disutility of time and effort, $C(m_i)$, as they need to allocate separate time and effort (in addition to their day-to-day activities) to identify, prepare, compile and upload the necessary digital twins into the BCFG-DTSF. Here, $C(\cdot)$ is increasing and convex in m_i, i.e., $C'(m_i) > 0$ and $C''(m_i) > 0$.

Now, consider the following scenario: First, BCFG-DTSF introduces the sharing incentive mechanism to motivate digital twin sharing. In response, DTPs decide their optimal m_i ($m_i > 0$) that maximizes their utility. In the case that $m_i = 0$ or a DTP i decides not to participate in digital twin sharing through BCFG-DTSF, its utility remains unaltered. Finally, the DTPs are given compensation for their contributions based on the established incentive mechanism.

4.3.3 Incentive mechanism for digital twin elicitation

Given that E_i is the compensation DTP i becomes eligible to receive based on the incentive mechanism, the DTP decides the optimal sharing amount that maximizes its utility. When it decides to share m_i units of digital twins, it incurs a cost $C(m_i)$ and experiences a decrease in its utility of privacy to $B(n_i - m_i)$ while receiving a compensation $\mathrm{E}_i(m_i)$. Hence, DTP i maximizes its net utility:

$$\max_{m_i} Z = B(n_i - m_i) - C(m_i) + \mathrm{E}_i \tag{1}$$

The first-order condition for (1) is given by:

$$\frac{\partial B(n_i - m_i)}{\partial m_i} - C'(m_i) + \frac{\partial \mathrm{E}_i}{\partial m_i} = 0 \tag{2}$$

(2) has an economic intuition. It balances the marginal benefits of digital twin sharing, $\frac{\partial R_i(m_i)}{\partial m_i}$,against the marginal costs $C'(m_i)$ (cost of time and effort) and $-\frac{\partial B(\boldsymbol{n}_i - m_i)}{\partial m_i}$ (drop in the utility of privacy). Knowing that DTPs aim to maximize their net utility, BCFG-DTSF tries to maximize its net payoff given by:

$$\max_{\substack{m_1 \dots m_x \\ R_1 \dots R_x}} \pi = V(m) - \sum_{i=1}^{x} \mathrm{E}_i \tag{3}$$

s.t.

$$B(n_i - m_i) - C(m_i) + \mathrm{E}_i \geq B(n_i);\ \forall i \quad (4)$$

$$\frac{\partial B(n_i - m_i)}{\partial m_i} - C'(m_i) + \frac{\partial \mathrm{E}_i}{\partial m_i} = 0;\ \forall i \quad (5)$$

where (4) and (5) represent the individual rationality constraint (IRC) and incentive compatibility constraint (ICC), respectively, of DTP i [66]. Here, IRC represents the DTP's expectation to experience a non-negative utility from digital twin sharing, whereas ICC shows that the DTP always share digital twin amounts optimal to them (i.e. they share the amount m_i that maximize their utility). Using binding participation constraint (4) on (3), the first-order condition for the BCFG-DTSF's problem at the optimum may be written as:

$$\frac{\partial V(m)}{\partial m_i} + \frac{\partial B(n_i - m_i)}{\partial m_i} - C'(m_i) = 0;\ \forall i \quad (6)$$

(6) has its economic intuition. It balances the marginal benefits of the BCFG-DTSF (increase in payoff $\frac{\partial V(\boldsymbol{m})}{\partial m_i}$) with the costs ($-\frac{\partial B(n_i - m_i)}{\partial m_i} + C'(m_i)$) associated with digital twin sharing. Hence, at optimum, the marginal benefits from a unit increase in digital twin sharing balance out the corresponding marginal costs. Additionally, the partial derivative of equation (6) on m_i being nonnegative means that (3) satisfies the second-order conditions.

If $\boldsymbol{m}^* = (m_1{}^*, m_2{}^* \ldots\ldots m_x{}^*)$ represents the optimal digital twin sharing by the DTPs based on the solution of the BCFG-DTSF's first-order condition, using (5) and (6) alongside the binding participation constraint (4) results in the incentive-compatible system for digital twin sharing described in the proposition below.

Proposition: The incentive-compatible digital twin sharing mechanism is described as:

$$\mathrm{E}_i(m_i) = f_i m_i + g_i \quad (7)$$

where

$$f_i = \frac{\partial V(\boldsymbol{m}^*)}{\partial m_i}\, m_i$$

$$g_i = B(n_i) - B(n_i - m_i{}^*) + C(m_i{}^*) - \frac{\partial V(\boldsymbol{m}^*)}{\partial m_i}\, m_i{}^*$$

(7) gives an incentive-compatible digital twin sharing system linear in m_i. Although we did not predefine the functional form of R_i, the use of the expression $\mathrm{E}_i(m_i)$ is based on the dependence revealed by (7).

Here, f_i and g_i are the fixed and variable components of the compensation provided, with f_i accounting for the marginal value and g_i representing the base value assigned to DTP i for its digital twin contribution. Interestingly, the compensation received by DTP i is observed to be dependent on the amount of digital twins shared m_i and its productivity or marginal contribution to the financial performance of BCFG-DTSF, $\frac{\partial V(\boldsymbol{m}^*)}{\partial m_i}$, at the optimum.

As an extension, assuming all the DTPs exhibit their optimal behavior by sharing their optimal amount of digital twins, $m_i{}^*(i = 1,2 \ldots x)$, (7) can be rewritten as:

$$\mathrm{E}_i(m_i{}^*) = B(n_i) - B(n_i - m_i{}^*) + C(m_i{}^*) \tag{8}$$

$$\pi^* = V(\boldsymbol{m}^*) - \sum_{i=1}^{x} B(n_i) - B(n_i - m_i{}^*) + C(m_i{}^*) \tag{9}$$

From (8), it becomes clear that at the optimum, DTPs enjoy net-zero utility (i.e., $Z^* = B(n_i)$) if they decide to contribute $m_i{}^*$ amount of digital twins and negative net utility otherwise, as shown in Fig. 3 (refer to Appendix 2 for the functional forms used). In the case of SP, it enjoys a net surplus that is equal to the overall gains made from the digital twins, $V(\boldsymbol{m}^*)$, minus the compensation given to the DTPs, $\mathrm{E}_i(m_i{}^*)$.

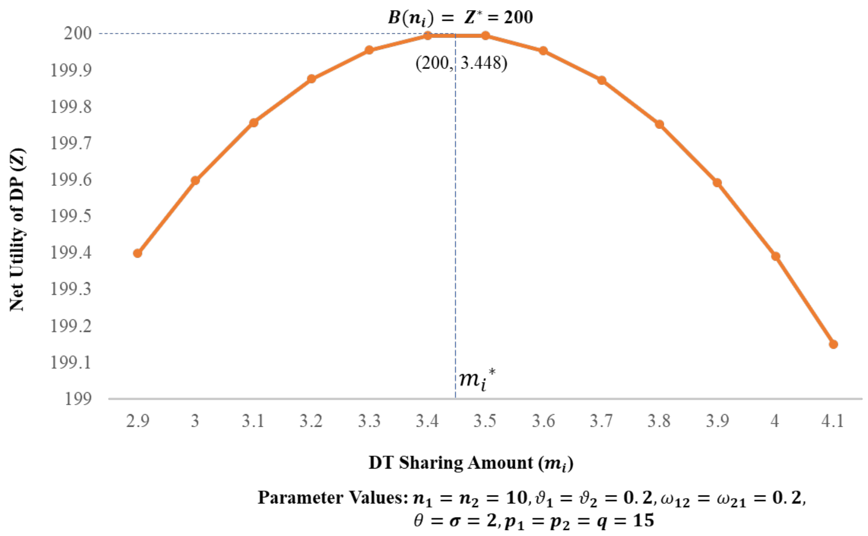


Fig. 3. The effect of digital twin sharing on the net utility of DTPs

5. DEMONSTRATIVE CASE STUDY

To verify and evaluate BCFG-DTSF, a demonstrative case study is conducted in a laboratory environment. As a typical kind of social manufacturing resources, 3D printers are taken to realize the referential digital twin model using MVC-DDD. A prototype system for BCFG-DTSF is developed and implemented to support digital twin sharing among social communities. The system performance is evaluated and analyzed using the above prototype.

5.1. Digital twin implementation

To verify the proposed digital twin architecture, three 3D printers are selected to illustrate the scalability and reconfigurability from MVC aspect and domain aspect separately. The specifications of these printers are summarized in Table 2. The selected 3D printers all have their own customized features so that their digital twin systems will be accordingly different in terms of granules. SHDM 3DDTP-500 is a generic 3D printers, which can be regarded as the basic digital twin for FDM (Melt deposition molding) printers. The additional features of JGAurora Z-603s affect the Control Context in Enabling Domain so that we will just extend this granule or reconfigure its specific MVC elements accordingly. Since bounded context are coupled via RESTful APIs, the changes in this granule will not influence others, to make each granule separate. By abstracting the common features of these printers, nine general microservices are designed for each bounded context in Fig. 1. The overall implementation architecture is illustrated in Fig. 4. Since each microservice is loosely coupled, it can be reconfigured according to specific features of a 3D printer. Benefiting from MVC, a microservice is also easily scalable with development of discrepant elements. For example, the appearance context is a case-by-case digital twin granule among printers with different types and brands. To be more specific, the control logic and interaction view for this context is almost the same besides the geometry models. Thus, we developed corresponding geometry models in the appearance context for these three printers to realize a uniform digital twin interaction. Since bounded contexts are loosely coupled via RESTful APIs, it is flexible to reconfigure the fine-grained shared contexts for constructing digital twin instances for social manufacturing resources. For example, the appearance context can be easily adjusted for Web or mobile environment.

Table 2. Specifications of 3D printers

	SHDM 3DDTP-500	JGAurora Z-603s	BlueMaker BM10-450
Printing Volume	500*500*600 mm	280 x 180 x 180 mm	300*350*450 mm
Printing Speed	60~120 mm/s	Up to 300 mm/s	30-400 mm/s
Layer Resolution	0.05 mm~0.4 mm	0.1mm ~ 0.3 mm	0.02 mm~0.4 mm
Nozzle Diameter	0.4~0.8 mm	0.4mm	0.1~1.0 mm
Additional Features	Nil.	(1) LED light control (2) Heat bed control (3) Fan speed control (4) Printing speed control	(1) Dual nozzles (2) Heat bed control (3) Fan speed control

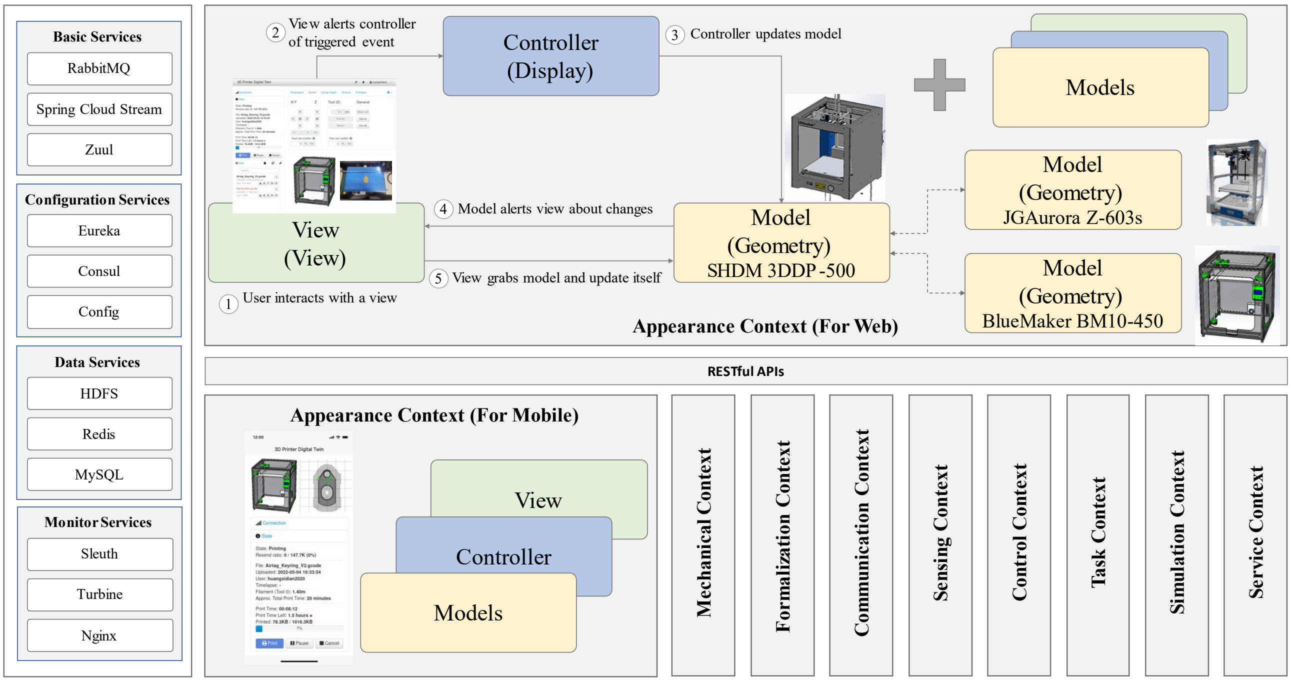


Fig. 4. A sample digital twin implementation for 3D printers

5.2. Prototype system demonstration

The system demonstration follows the business logic of BaaS. The first phase is for the owner of a digital twin model to encapsulate the intended digital twin granules, as shown in Fig. 5. The owner of a digital twin model based on our referential digital twin architecture can select a bounded context to share with three steps. First, the basic description is defined. Then, the dependencies of this context during deployment and execution are configured. Finally, the environmental parameters are set to wrap the context into digital twin granules.

Fig. 5. Digital twin contribution operations

The second phase registers the encapsulated digital twin granule with an on-chain copyright proof, as illustrated in Fig. 6. This phase also has three steps. First, only the encapsulated context can be registered on the blockchain. Meanwhile, the prototype also supports the registration of self-encapsulated digital twin granules. The second step is to configure the parameters for proof generation, including the backend algorithm, hash algorithm, user password, and private key. Third, to put the generated proof on the blockchain, the related settings for the target chain are required.

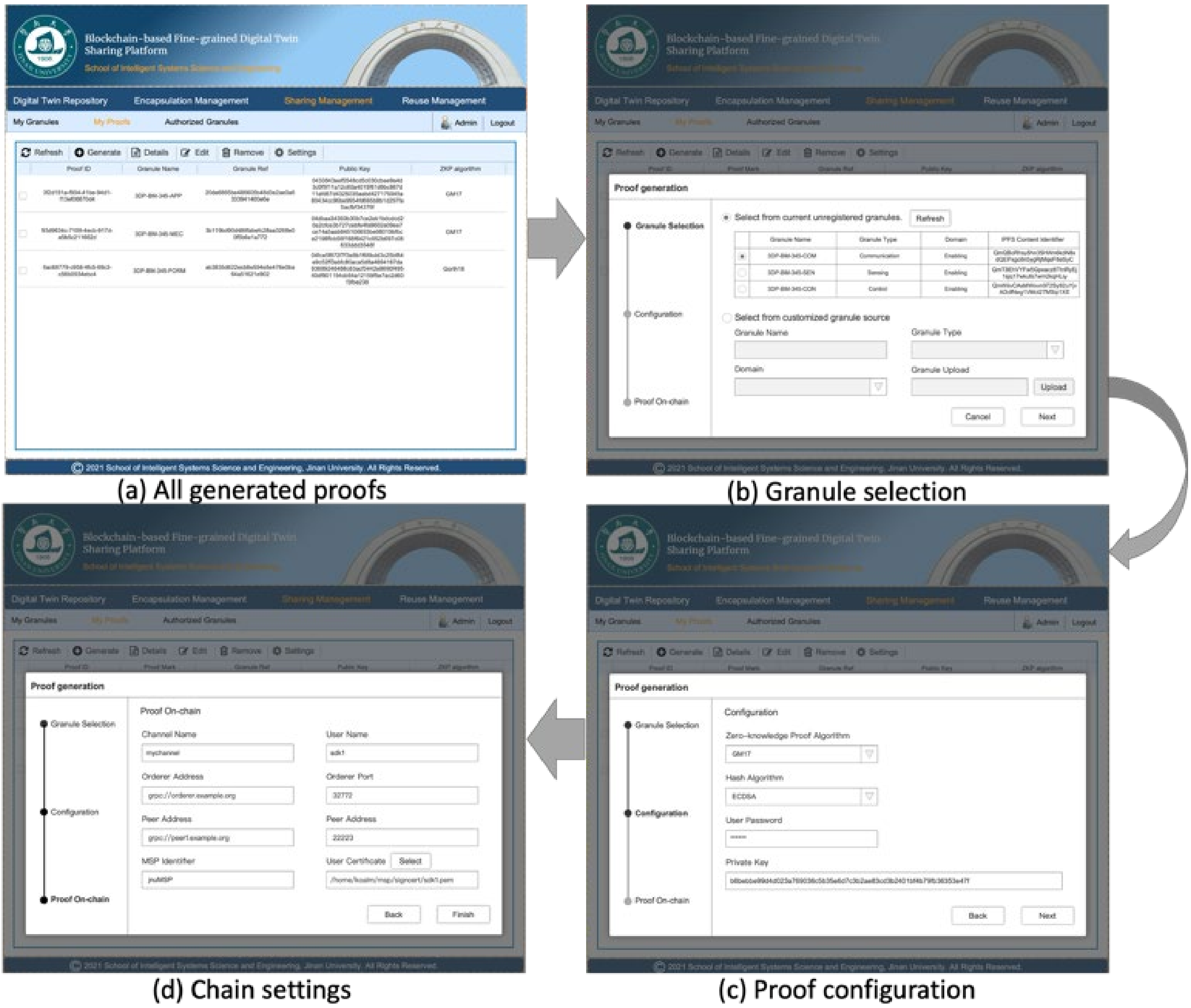
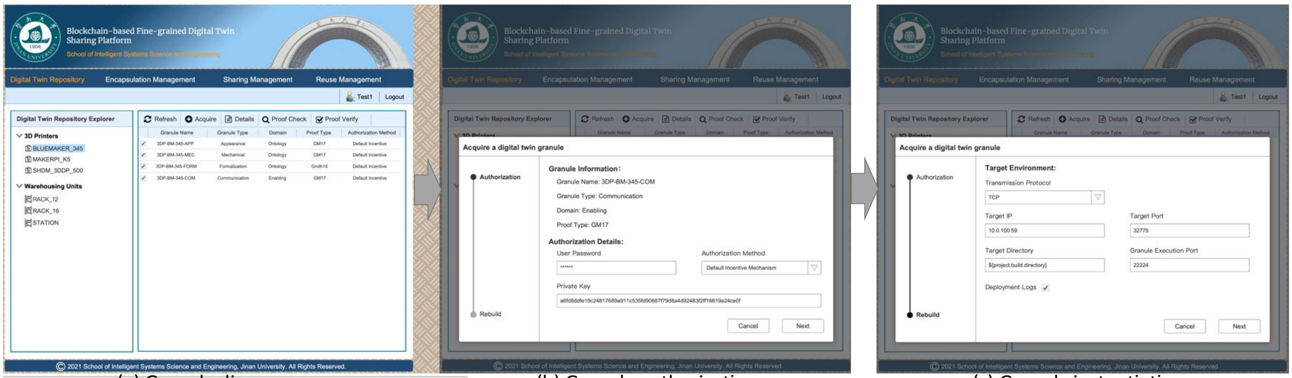


Fig. 6. Digital twin sharing

In the third phase, the demand side can search the desired granules for its digital twin in the sharing repository via the granule discovery service. Then, the authorization of a digital twin granule is made under *Mechanism 3* and *4*. Finally, if authorized, the demand will hold the proof to request the compilable source of a digital twin granule via *Mechanism 5*, if proof verification pass using *Mechanism 6,* the system will rebuild the granule and generate executable instances according to the target running environment and transmits to the demander. All the processes are displayed in Fig. 7.



(a) Granule discovery (b) Granule authorization (c) Granule instantiation

Fig. 7. Digital twin reuse

5.3. Performance evaluation

To further evaluate the computing performance of prototype system, a testing environment is established to explore the tangible and practical implications for sharing digital twin granules. The development tools for this testing environment are based on Python 3.8, Flask 1.1.2, ZoKrates 0.7.7, SQLite3 2.6.0 and FISCO BCOS v.2.9.0. The hardware specification and basic experiment settings are illustrated in Table. 3. The computing performance of this system is evaluated based on three aspects.

Table 3. Basic Experimental Environment and Settings

Hardware Platform	Dell T7920 Workstation (Intel Xeon Gold 6230R*2, 128 GB RAM, 1 TB SSD)
Operating System	Hypervisor: ESXi 6.7u3
Virtual Machine	4 vCPUs, 4 GB RAM, 40 GB SSD, Ubuntu 18.04
Network	10 Gb vSwitch & pfSense V2.0.5
Orderer Type	PBFT
Database Type	LevelDB
Batch Timeout	2 s
Max Message Count	500
Absolute Max Bytes	20 MB
Preferred Max Bytes	512 KB
Endorsement Policy	1 of N

First, the blockchain performance for digital twin granule registration is tested under different sending rates and block sizes using the Groth 16 ZKP scheme, as shown in Table 4. The average processing time for each block is taken as the key indicator to measure system performance because it better approximates the user experience to represent the response time of a user request until it is on the chain. This result conforms to the regular blockchain principle that the larger the block size, the better the throughput performance will be. However, it will lead to longer latency because a block must collect enough transactions for consensus operation. Meanwhile, we also found that when the number of transactions in a block are four times the sending rate, the average processing time is almost the same and the best, indicating that the system works in an optimal condition. In particular, the block size can also be set as two times the value of the sending rate to avoid the uncertain latency incurred by a large block size.

Table 4. Average processing time using Groth 16 (second)

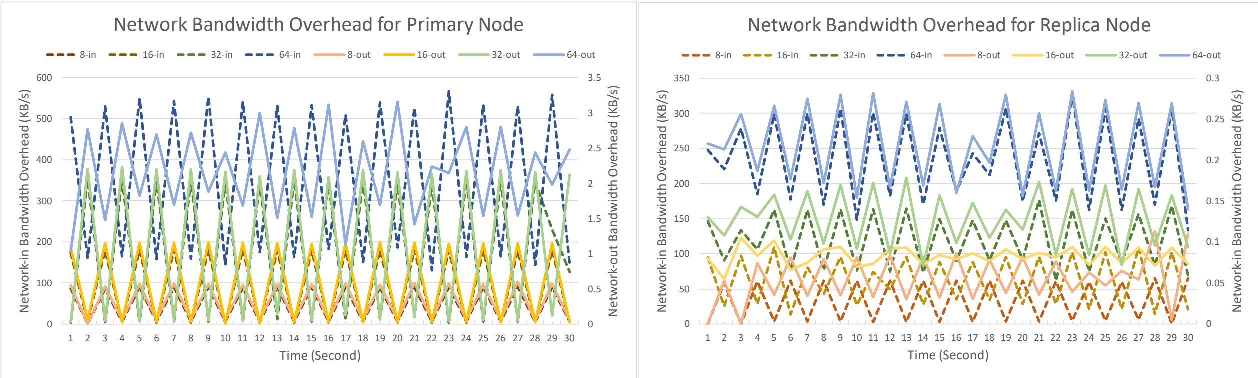
Block Size (Transactions/Block)	Sending Rate (Transactions/Second)				
	2	4	8	16	32
8	**5.73**	6.73	67.42	113.25	134.94
16	7.76	**5.74**	5.79	38.86	59.01
32	11.79	7.84	5.77	**5.17**	22.29
64	19.95	11.95	7.77	**5.74**	6.19

Second, we compare the specific performance of using two ZKP algorithms, Groth16 [67] and GM17 [68]. The computing performance for three key proof operations is summarized in Table IV. Two hundred sets of proof generation and verification are tested for registration, authorization and instantiation, and the average processing time is generated. The experiments results have revealed that both algorithms have the similar proof verification performance, while the proof generation time

Table 5. Performance comparison between different ZKP algorithms

Average Processing Time	Groth16 (seconds)	GM17 (seconds)
Registration Generation	10.1255	99.7728
Registration Verification	0.0203	0.0198
Authorization Generation	57.9232	533.1922
Authorization Verification	0.0198	0.0213
Instantiation Generation	55.2223	493.6625
Instantiation Verification	0.0211	0.0208

differs a lot. Groth 16 is more efficient in our system, but it's security risk should be further concerned for large-scale application since its proof is vulnerable to the malleability attacks [69].



(A) NETWORK BANDWIDTH OVERHEAD FOR THE PRIMARY NODE

(B) NETWORK BANDWIDTH OVERHEAD FOR THE REPLICA NODE

Fig. 8. Network bandwidth overhead for different sending rates

Third, the network bandwidth overhead is measured under different sending rates when the block size is set to 8 transactions. As shown in Fig. 8, the bandwidth overhead has a positive correlation with the sending rates. Since we take proofs instead of digital twin granules themselves for blockchain network transmission, the small size of proofs greatly reduces network bandwidth consumption. In addition, the inbound and outbound network bandwidth follows a fixed proportion because the message content and distribution scheme in practical Byzantine fault tolerance (PBFT) are stable.

5.4. Analysis of the sharing incentive mechanism

In this section, we analyze the performance of the incentive mechanism with respect to changes in amount, productively and interdependence of a DTP's digital twins. Consider an increase in productivity of DTP i, $\frac{\partial V(\boldsymbol{m};\boldsymbol{n})}{\partial m_i}$, with the productivities of all other DTPs remaining unchanged. Here, the left-hand side of (6) exhibits a positive value at $\boldsymbol{m}^*$. This forces the rest of the DTPs to increase their digital twin sharing amounts in their first-order conditions (owing to positive interdependence) from ${m_j}^*$ $(j \neq i)$ to ensure that (6) holds. This calls for an increase in $\frac{\partial V(\boldsymbol{m})}{\partial m_i}$ $(i = 1,2,3 \ldots x)$ to compensate for the decrease in $\frac{\partial B(\boldsymbol{n}_i - m_i)}{\partial m_i} - C'(m_i)$ at the optimum. Therefore, an increase in productivity of DTP i produces an increase in the marginal benefits extended to DTP i as well as the other DTPs.

Now, the impact of the amount and productivity of digital twins held by DTP i on the optimal amount of digital twins shared, $m_i{}^*$, is given in the following lemma (refer to Appendix 1 for the proof).

Lemma. The optimal amount of digital twins shared by DTP i, $m_i{}^*$, is introduced in Table 6.

Table 6. Analysis of Optimal digital twin Sharing

Amount of digital twins	*Interdependence* $\left(\frac{\partial^2 V(\boldsymbol{m};\boldsymbol{n})}{\partial m_i \partial m_j}\right)$	*Productivity of digital twin (PD)*		
		$PD_i > PD_j$	$PD_i = PD_j$	$PD_i < PD_j$
$n_i = n_j$	≥ 0	$m_i{}^* > m_j{}^*$	$m_i{}^* = m_j{}^*$	$m_i{}^* < m_j{}^*$
$n_i > n_j$	$= 0$	$m_i{}^* > m_j{}^*$	$m_i{}^* > m_j{}^*$	Mostly $m_i{}^* > m_j{}^*$
	> 0	$m_i{}^* > m_j{}^*$ (mostly)	$m_i{}^* > m_j{}^*$ (mostly)	Intermediate

Irrespective of the interdependence, a more productive DTP shares a larger amount of digital twins than the DTPs with lower productivity when all the DTPs possess the same amount of digital twins (i.e., $g_i = g_j$ for all $i \neq j$), as seen from the first row.

Furthermore, to set up the incentive mechanism for different levels of interdependence, consider that DTP i holds digital twins of higher productivity than those of DTP j (i.e., $PD_i > PD_j$). Here, $m_i{}^* > m_j{}^*$ at the optimum. Examining (1.1) in Appendix 1 indicates that the net value of the terms in the first parenthesis is always positive because the net values of terms within the second and third parentheses are negative and positive, respectively. As a result, $f_i(= \partial V(\boldsymbol{m}^*)/\partial m_i) > f_j(= \partial V(\boldsymbol{m}^*)/\partial m_j)$. If we assume $g_i \geq g_j$, $\mathrm{E}_i(m_i) = f_i m_i + g_i > \mathrm{E}_j(m_i) = f_j m_i + g_j$ for all m_i. In contradiction to the result from section 6.3 (DTP's experience net-zero utility at the optimum), $\mathrm{E}_i(m_j{}^*) = f_i m_j{}^* + g_i > \mathrm{E}_j(m_j{}^*) = B(n) - B(n - m_j{}^*) + C_{DP}(m_j{}^*)$; i.e., the DTP i that shares $h_j{}^*$ amount of digital twins experiences a net positive utility. Hence, the value of g_i should be less than g_j. Consequently, when the DTPs exhibit homogeneity over all other factors, the DTP i with higher productivity should be rewarded with a higher marginal value, f_i, and lower base value, g_i, than DTP j under the proposed incentive mechanism.

Now, we focus on the scenario where a DTP i holds more digital twins than DTP j (i.e., $n_i > n_j$) in the second row of Table 1. Here, the marginal cost of digital twin sharing for DTP i is less than that for DTP j. Furthermore, for zero interdependence and $MP_i \geq MP_j$, digital twins from DTP i have a larger impact on the platform's payoff than those from DTP j. Hence, to establish a balance between cost and benefits as introduced in (6), the platform promotes higher digital twin sharing from DTP i than from DTP j (i.e., $m_i{}^* > m_j{}^*$). For all other cases/scenarios introduced in the lemma, a unique relation between $m_i{}^*$and $m_j{}^*$ does not exist, although $m_i{}^* > m_j{}^*$holds for most of the cases.

In summary, the incentive mechanism prioritizes DTPs that hold more digital twins or more productive digital twins for higher digital twin sharing into the blockchain platform. A DTP that holds more digital twins' experiences relatively lower disutility from sharing its digital twins, whereas its productivity positively influences the platform payoff/performance. Notably, all the DTPs receive a fair value for their contribution, irrespective of the amount of digital twins they hold. A DTP with a considerable amount of digital twins gains more significant rewards for their contribution. On the other hand, a contributor with a smaller amount of digital twins earns from its interdependence with the contributor that holds digital twins in a more considerable amount. This feature of the incentive mechanism ensures that the BCFG-DTSF is not dominated or centralized by a few DTPs, with large digital twins accumulating all the rewards. Therefore, smaller DTPs, or even new DTPs, have the incentive to join and benefit from the BCFG-DTSF, thereby conserving the decentralized nature of the incentive mechanism over time.

6. CONCLUSION

To make sufficient use of sharing in social manufacturing, this paper has presented a novel sharing framework to facilitate the sharing of digital twin in a fine-grained manner. Three contributions have been made.

First, a novel design method, MVC-DDD, is proposed as the ingenious combination of MVC and DDD. The introduction of a domain is beneficial to address the complexity of digital twin and establish uniform understanding within a domain. It provides the basis to partition a digital twin into a fine-grained encapsulation. Then, MVC maintains a better scalability and maintainability to build a domain. It facilitates the continuous improvement and innovation of digital twin granules through the common interests and enthusiasms released by social manufacturing communities. Based on this design method, a referential digital twin architecture contributes a new guiding model of digital twin from the software architecture perspective, which makes community participants easily understand and promotes the creation of more digital twins. Second, the BCFG-DTSF has proposed a series of sharing mechanisms to take zero-knowledge proof as a carrier for sharing operations and blockchain as an execution environment for decentrailized proof verification. It provides a novel appraoch to realize a multiparty noncommutative information verification under a decentralized environment using ZKP. Third, we introduced an incentive mechanism to promote digital twin sharing. Despite its simplified nature, the model took into account various important characteristics/parameters such as a DTP's private utility from its digital twins, the cost of digital twin sharing, interdependence among digital twins, and the productivity of digital twins or its impact on the performance of the blockchain platform. It facilitates the sustainability of knowledge sharing of the social manufacturing. In addition, the tamper-resistant feature also makes an evidenced traceability and trackability for digital asset management, which could further guarantee the protection of intellectual property rights of digital assets, especially digital twins.

This paper can be extended from three directions. The first direction is the further division of sharing granules. Even though the current study defines the MVC elements in each domain, the smallest sharing granule is still the domain considering the reusability of encapsulation. Further exploration could be made on the standardized interoperable interfaces among MVC elements and service-oriented encapsulation methods. The second direction is to enlarge the verification scope to cover more kinds of digital twins. Limited by the laboratory environment, the reconfiguration and development of digital twins using the referential architecture are performed on several 3D printers and smart warehousing units. More physical social manufacturing resources are suggested to be digitalized into digital twins via this architecture. Third, further work should focus on improving the incentive mechanism while considering more real-life factors, such as the storage space contribution, multistakeholder equity distribution and other hidden transaction costs.

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APPENDIX 1- PROOF OF LEMMA

By equating first-order conditions for DTPs i and j as given in (6), we obtain

$$\left\{\frac{\partial V(\boldsymbol{m}^*;\boldsymbol{n})}{\partial m_i}-\frac{\partial V(\boldsymbol{m}^*;\boldsymbol{n})}{\partial m_j}\right\}+\left\{\frac{\partial B(n_i-m_i{}^*)}{\partial m_i}-\frac{\partial B\left(n_j-m_j{}^*\right)}{\partial m_j}\right\} \\ -\left\{C'(m_i{}^*)-C'\left(m_j{}^*\right)\right\}=0 \tag{1.1}$$

(1) **Case 1:** $n_i = n_j\ (= n)$. Considering $PD_i > PD_j$, suppose $m_i{}^* \leq m_j{}^*$. In (1.1), the net value of the terms in the first parenthesis is always positive because the net values of terms within the second and third parentheses are negative and positive, respectively. However,

$$\frac{\partial V\left(m_i{}^*,m_j{}^*;n,n\right)}{\partial m_i} \geq \frac{\partial V\left(m_j{}^*,m_j{}^*;n,n\right)}{\partial m_i} > \frac{\partial V\left(m_j{}^*,m_j{}^*;n,n\right)}{\partial m_j} \geq \frac{\partial V\left(m_i{}^*,m_j{}^*;n,n\right)}{\partial m_j} \tag{1.2}$$

which results in a contradiction (the combination of the concavity of V, the interdependence, and the productivity of i and j leads to inequality). Therefore, $m_i{}^* > m_j{}^*$.

Furthermore, when $PD_i = PD_j$, $m_i{}^* = m_j{}^*$by symmetry.

(2) **Case 2:** $n_i > n_j$. When $m_i{}^* \leq m_j{}^*$ (similar to Case 1), the net value of the terms in the first parenthesis of (1.1) maintains a negative value to satisfy the condition. Hence:

$$\frac{\partial V(m_i^*, m_j^*; n_i, n_j)}{\partial m_i} = \frac{\partial V(m_i^*, m_j^*; n_j, n_j)}{\partial m_i} \geq \frac{\partial V(m_j^*, m_j^*; n_j, n_j)}{\partial m_i} \quad (1.3)$$

- *Subcase 1*: *Zero interdependence* $\left(\partial^2 V(\boldsymbol{m}; \boldsymbol{n})/\partial m_i \partial m_j = 0\right)$. When interdependence does not exist:

$$\frac{\partial V(m_j^*, m_j^*; n_j, n_j)}{\partial m_j} = \frac{\partial V(m_i^*, m_j^*; n_i, n_j)}{\partial m_j} \quad (1.4)$$

If $PD_i \geq PD_j$, then $\partial V(m_j^*, m_j^*; n_j, n_j)/\partial m_i \geq \partial V(m_j^*, m_j^*; n_j, n_j)/\partial m_j$. Subsequently, as seen from (1.3) and (1.4), $V(m_i^*, m_j^*; n_i, n_j)/\partial m_i \geq \partial V(m_i^*, m_j^*; n_i, n_j)/\partial m_j$, which results in a contradiction. Therefore, $m_i^* > m_j^*$. If $PD_i < PD_j$, then $\partial V(m_j^*, m_j^*; n_j, n_j)/\partial m_i < \partial V(m_j^*, m_j^*; n_j, n_j)/\partial m_j$. By (1.3) and (1.4), $\partial V(m_i^*, m_j^*; n_i, n_j)/\partial m_i - \partial V(m_i^*, m_j^*; n_i, n_j)/\partial m_j$ turns negative only for a substantial productivity difference between DTPs i and j. Hence, $m_i^* > m_j^*$ for most of the cases as (1.1) fails to hold, with the exception arising (i.e., (6) holds or $m_i^* \leq m_j^*$) when a substantial productivity difference exists among DTPs.

- *Subcase 2*: *Positive interdependence* $\left(\partial^2 V(\boldsymbol{m}; \boldsymbol{n})/\partial m_i \partial m_j > 0\right)$. For this subcase, (1.4) could be modified as:

$$\frac{\partial V(m_j^*, m_j^*; n_j, n_j)}{\partial m_j} > \frac{\partial V(m_i^*, m_j^*; n_j, n_j)}{\partial m_j} < \frac{\partial V(m_i^*, m_j^*; n_i, n_j)}{\partial m_j} \quad (1.5)$$

When $PD_i \geq PD_j$, with (1.3) and (1.5) taken into account, $\partial V(m_i^*, m_j^*; n_i, n_j)/\partial m_i \geq \partial V(m_i^*, m_j^*; n_i, n_j)/\partial m_j$ is likely to hold when (i) n_i and n_j are very similar, i.e., $\partial V(m_i^*, m_j^*; n_i, n_j)/\partial m_j - \partial V(m_i^*, m_j^*; n_j, n_j)/\partial m_j$, that is not very large (from second inequality in (1.5)) or (ii) when the DTPs maintain low interdependence. Therefore, $m_i^* > m_j^*$ holds for most of the cases.

Now, for $PD_i < PD_j$, $\partial V(m_j^*, m_j^*; n_j, n_j)/\partial m_i < \partial V(m_j^*, m_j^*; n_j, n_j)/\partial m_j$. From (1.3) and (1.5), $\partial V(m_i^*, m_j^*; n_i, n_j)/\partial m_i - \partial V(m_i^*, m_j^*; n_i, n_j)/\partial m_j$ turns negative for a large difference in productivity and insignificant interdependence among DTPs. Hence, $m_i^* \leq m_j^*$ holds only when a significant difference in productivity exists between the DTPs. As a result, (1.1) is not satisfied in most of the cases, producing $m_i^* > m_j^*$.

APPENDIX 2-FUNCTIONAL FORMS

The functional forms used for plotting Fig. 2 include:

$$V(\boldsymbol{m}) = \sum_i (\vartheta_i/2)\,({p_i}^2 - (p_i - m_i)^2) \sum_{j \neq i} n_j + \sum_i \sum_{j>i} \omega_{ij} m_i m_j$$

$$p_i \geq n_i, \vartheta_i > 0 \text{ and } \omega_{ij} > 0 \text{ for all } i \neq j. \tag{1.6}$$

$$B(n_i) = (\theta/2)(q^2 - (q - n_i)^2), \theta > 0 \text{ and } q \geq n_i \text{ for all } i. \tag{1.7}$$

$$C(m_i) = (\sigma/2){m_i}^2, \sigma > 0. \tag{1.8}$$

Therefore,

$$\partial V(\boldsymbol{m})/\partial m_i = \vartheta_i (p_i - m_i) \sum_{j \neq i} n_j + \sum_{j \neq i} \omega_{ij} m_j,$$

The parameters ϑ_i and ω_{ij} stand for the productivity of digital twins. Here, the productivity of m_i realizes an increase with the increase in ϑ_i and ω_{ij}. Additionally, $\partial^2 V(\boldsymbol{m})/\partial m_i \partial m_j = \omega_{ij}$. Hence, ω_{ij} addresses the interdependence between digital twins of DTP i and DTP j. Now, the significance of privacy and effort is given by θ and σ, respectively.

Here, we derive the optimal solutions for a platform with two DTPs ($x = 2$). We avoid the derivation for more than two DTPs to conserve space.

Since $B(n_i - m_i)/\partial m_i = -\theta(q - n_i + m_i)$ and $C'(m_i) = \sigma m_i$, (6) for DTP i becomes:

$$\vartheta_i n_{3-i}(p_i - m_i) + \omega_{12} m_{3-i} - \theta(q - n_i + m_i) - \sigma m_i = 0, i = 1{,}2. \tag{1.9}$$

Solving the first-order conditions for two DTPs in (1.9) simultaneously,

$$\begin{aligned} {m_i}^* = {} & \frac{\vartheta_{3-i}\theta {n_i}^2 + (\vartheta_i \vartheta_{3-i} p_i n_{3-i} + \vartheta_{3-i}\omega_{12} p_{3-i} - (\vartheta_{3-i} q - \theta - \sigma)\theta) n_i}{(\vartheta_{3-i} n_i + \theta + \sigma)(\vartheta_i n_{3-i} + \theta + \sigma) - {\omega_{12}}^2} \\ & + \frac{(\vartheta_i p_i(\theta + \sigma) + \omega_{12}\theta) n_{3-i} - (\omega_{12} + \theta + \sigma)\theta q}{(\vartheta_{3-i} n_i + \theta + \sigma)(\vartheta_i n_{3-i} + \theta + \sigma) - {\omega_{12}}^2}, i = 1{,}2. \end{aligned} \tag{1.10}$$

Plugging ${m_i}^*$ from (1.10) into $\partial V(\boldsymbol{m})/\partial m_i$, $B(n_i - m_i)$, and $C(m_i)$, we obtain the marginal value $f_i = \partial V(\boldsymbol{m}^*)/\partial m_i$, and the base value $g_i = B(n_i) - B(n_i - {m_i}^*) + C({m_i}^*) - (\partial V(\boldsymbol{m}^*)/\partial m_i){m_i}^*$. To conserve space, we omit the detailed expressions.

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