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Makerchain: A blockchain with chemical signature for self-organizing process in social manufacturing

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ABSTRACT

The growth of personalized demands requires socialized resources to timely self-organize themselves with crowd intelligence for co-creating open architecture products. This social manufacturing paradigm drives an increased demand for makers to track the authenticity and quality of products. A new decentralized blockchain-driven model, named Makerchain, is presented to handle the cyber-credit of social manufacturing among various makers. An anti-counterfeiting method composed of chemical signature is proposed to represent unique features of personalized products. Twinning unique signature data to blockchain and other functional databases is realized and anticipated to make manufacturing service transactions among makers more trustworthy. Based on an automated execution mechanism of smart contracts among makers, a decentralized manufacturing network can be enabled for automating transactions among makers, as well as third-party verification of product lifecycle through a trail of historic events. A Makerchain Decentralized Application (DApp) is presented to demonstrate the proposed approach through which clustered makers can self-organizing themselves around personalized demands.

1. Introduction

The rapid development of cheap small-size rapid prototyping tools such as 3D printers has made product development more open and socialized. The decentralized collaborative manufacturing of open architecture products is of great significance for improving of products as well as meeting massive personalized demands (Koren et al., 2013). Various social manufacturing networks composed of makers and prosumers are emerging, which greatly brings challenge to traditional large manufacturers previously in a dominant position (Jiang et al., 2016). Social manufacturing could offer system-level changes by activating and empowering the end consumers to become value creators, while forming considerable innovative sustainable outcomes in design and manufacturing (Hirscher et al., 2018; Hamalainen et al., 2018). It is a novel decentralized collaborative paradigm rather than a hierarchical and top-down cooperating structure.

Ensuring trust among makers in a social manufacturing paradigm is challenging, since multiple distributed makers are involved in the design, manufacturing, and assemblies of product (Hamalainen et al., 2018). Conventionally, trust in a manufacturing community is formed via extensive contract bargain and negotiation, acknowledgement of historic credit report, and periodic financial audits. Traditional methods in establishing trust will hinder the economic feasibility of social manufacturing paradigm. The costs of securing trust among all makers is significant. Moreover, although the open architecture-type of products can guarantee the industry standards and interfaces in a social manufacturing paradigm, it is still difficult to obtain an effective interconnection among makers due to the lack of decision-supporting mechanism to form consensus. In the blueprint of Industry 4.0, it is envisioned that rapid commissioning and decommissioning of participates are enabled to save effort and cost

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on ensuring trust in a decentralized manufacturing paradigm (Wang et al., 2016). It is necessary to explore a self-organizing method that adapts to the decentralizing characteristics of collaboration.

Blockchain can potentially meet the demand of decentralized collaboration, which is the securing of trust from the technical level (Apte and Petrovsky, 2016; Yli-Huumo et al., 2016). Possessing the advantage of distributed consensus and tampering-resistant, blockchain makes decentralized and autonomous manufacturing collaboration possible. Fusion of industrial Internet and blockchain can create a digital twin of the physical space and establish an online decentralized social manufacturing network (Tao et al., 2018). Image a case that a part in a product broke down in-situ far from the company without spare parts on hand. But we have a 3D printer and enough material. We can remotely print out new part with full compliance of demands based on a kind of decentralized trust in blockchain-driven environment. All parts are no longer maintained with certain specified factory, but by many distributed makers with credit. In this demands-driven digital social manufacturing context, expect for the storage cost of raw materials, it will be able to save a large amount of warehousing cost of final products, effort on logistics, and long-time paperwork for passing the regulations. Especially, some high-end products such as aircraft parts should be legally traceable with a “birth certificate” detailing how the parts were manufactured as well as the specifications. Smart contract in blockchain may bring us added-value to form a trust relationship (Hirscher et al., 2018).

However, there two challenges hindering the implementation of blockchain and smart contracts in social manufacturing paradigm. Firstly, although the blockchain is superior for recording the lifecycle events of a workpiece, a requirement for physical verification of workpieces in blockchain system still exists, which would greatly cut down counterfeits and save cost on ensuring trust (Kennedy et al., 2017). However, since the physical features are usually designed for meeting certain function and performance goals, the chemical signature is a better choice for anti-counterfeiting as it does not affect the original geometry of part design. Secondly, the existing blockchain platform has no complete set of solutions for mapping the manufacturing service relationships into the digital world (Zhang et al., 2017d).

To address the challenge of ensuring trust among makers in the social manufacturing paradigm, a blockchain-driven decentralized self-organizing model named Makerchain, through which a decentralized network of makers can cooperate in a manufacturing eco-system, is proposed. Key enabling techniques are detailed. Firstly, the blockchain data model and verification of manufacturing event is achieved. Secondly, the chemical signature technique is integrated with the consensus algorithm to enhance blockchain integrity. Thirdly, a smart contract tree model is proposed to enable makers autonomously interact on a decentralized network. Finally, a decentralized application is presented to demonstrate how demands can be fulfilled via the code-based smart contracts among makers. These key-enabling techniques can help move the innovative Makerchain model to mainstream decentralized manufacturing section. The implementation of the Makerchain is validated via a case study of 3D printer manufacturing based on an open source project named RepRap.

The rest of this paper is organized as follows. After a literature review on the digital twin and blockchain in manufacturing in section 2, section 3 presents a Makerchain model for decentralized social manufacturing. Aiming at preparing theoretically-grounded solutions for practical purposes, key enabling techniques including chemical signature, consensus algorithm, and smart contract are discussed in section 4 and 5, respectively. A demonstrative decentralized application is provided in section 6. Finally, the conclusions are presented in Section 7.

2. Literature review

There is an urgent requirement for sustainable manufacturing solution to be successful in increasing personalized demands (Ren et al., 2019). Since the Social Manufacturing vision has been proposed by the Economist magazine in 2012, scholars have built a variety of blueprint. Jiang et al. (2016) proposed the crowdsourcing-driven and community-based social manufacturing model. Other similar concept includes Maker Manufacturing proposed by Johar et al. (2015), Peer Production proposed by Kostakis and Papachristou (2014), Open Production proposed by Wulfsberg et al. (2011), and Crowd-Manufacturing proposed by Bonvoisin and Boujut (2015). The similarity of above concept lies in the crowded, clustered and decentralized characteristics of manufacturing interconnection (Leng and Jiang, 2018). While these new concepts are still evolving, the trend of mass personalization of open source/architecture products is very clear.

Scholars tried to realize mass personalization in different paradigms (Zhang et al., 2014). Since the manufacturing strategy is driven by the business context, Koren et al. (2013) studied on the cross-enterprise framework of mass personalization. Wang (2012) attempted to figure out how to use social networks in the 3D printing. Ren et al. (2015) presented a cloud manufacturing platform for small- and medium-sized enterprises. Barnaghi et al. (2015) proposed physical-cyber-social computing model to provide contextual awareness for proactive decision-making. Wang (2010) proposed cyber-physical-social system (CPSS) to achieve intelligence when systems are able to autonomously identify what's happening. Hussein et al. (2015) proposed a CPSS implementation model named Dynamic Social Structure of Things and verified it in an airport. However, the implementation of CPSS in manufacturing needs accessing a large infrastructure equipped with processors and sensors that can communicate with humans as well as forming big data (Zhang et al., 2017c, 2017d).

As mass personalized manufacturing continues to gain traction, the need of product traceability and counterfeiting increases. Barcodes and Radio-frequency identification (RFID) are two common technologies used to deliver traceability (Huang et al., 2009). Barcoding is a common and cost-effective method used as a pointer to implement traceability at both the item and case-level. It can be printed via laser marking, thermal transfer and direct thermal. RFID is a code-carrying technology used with track-and-trace solutions. It has been inhibited by certain limitations: tag cost, tag readability and privacy issues. Packing density and materials have a significant detrimental effect on read reliability of passive tags (Juels, 2006). Actually, counterfeiting of product is a relative more serious problem. For instance, the RFID tag is physically attached with workpieces and may be replaced by other fake tags (Choi et al., 2015). To improve the anti-counterfeiting ability, the selected areas of product are usually marked by 3D printing or adding additives (*e.g.*, holograms, engineered particulate, and taggant materials) (Kennedy et al., 2017). However, using highly-complicated additives in products will make the authentication too time-consuming and costly for end-users. As products are typically manufactured from plastic or metal, a more general anti-counterfeiting method is desirable.

Blockchain was invented by Satoshi Nakamoto in 2008 to serve as the public transaction ledger of the cryptocurrency Bitcoin (Nakamoto, 2008). A blockchain is a growing list of cryptography-linked records/blocks, each of which contains a cryptographic hash of the previous block, a timestamp, and transaction data (Zhao et al., 2016). A blockchain is usually managed by a peer-to-peer network collectively adhering to an inter-node communication protocol for validating new blocks (Underwood, 2016). The recorded block data cannot be altered retroactively without alteration of all subsequent blocks, which requires consensus of the network nodes. Blockchain can be act as an open and distributed ledger to record transactions between two parties in a verifiable and permanent way. Smart contract is actually a program that runs on the blockchain and has its correct execution enforced by the consensus protocol (Androulaki et al., 2018). It gains its security and trust from the blockchain and the underlying consensus among the peers (Christidis and Devetsikiotis, 2016). Decentralization is the core value of blockchain. By enabling decentralized nodes to dynamically collaborate and complete complex tasks with typical self-organization and adaptability, building smart contracts on the blockchain can realize consensus-based agreements.

Projects including Ethereum and Fabric build the open-source and cross-industry blockchain platform for use beyond crypto-currency, such as manufacturing. For instances, Apte and Petrovsky (2016) introduced blockchain into supply chain management to establish the trustiness, thereby denying a network for illegal and counterfeit products. Current implementations of blockchain usually rely on the basic blockchain infrastructure such as Fabric (Androulaki et al., 2018). The key to reduce the complexities of mass personalization is to improve flexibility of work-in-process flow for personalized demands, in which blockchain-driven decentralized management model is a potential solution.

It requires significant research in enabling blockchain applications truly interact with other systems in a decentralized manufacturing ecosystem. It is also critical to build self-organizing mechanism of manufacturing service, and thereby establish its operation techniques. This paper utilizes blockchain-driven smart contracts for decentralized self-organizing in social manufacturing of product architecture products, as well as saving cost on ensuring trust. A low-cost and easy-implementing carbon dots-based chemical signature is incorporated with physical QR code and blockchain to improve workpiece lifecycle security and prevent counterfeits.

3. Makerchain model for decentralized social manufacturing

3.1. Rationale of the makerchain

A Makerchain model for mass personalization is proposed as shown in Fig. 1. The Makerchain is a dynamic community of interrelated designer, demander, manufacturer, prosumer, verifier, regulator, and various makers in the decentralized network with a common goal of manufacturing personalized products in an open architecture. Blockchain provides an online environment for enabling the self-organization among makers in the Makerchain.

A crowd of decentralized makers self-organize themselves within the Makerchain to collaboratively processing tasks/demands with periodic confirmation and adjustment from verifiers and regulators. The personalized manufacturing tasks/demands can be matched to one suitable maker based on smart contracts and decentralized applications. Each maker can act as a blockchain node possessing the computing, storing, and networking service to manage a number of machines, equipment, and workpieces. Each maker will have a unique address identifying itself and synchronize a copy of all blocks as member of the Makerchain. Makers with verified manufacturing service capabilities can be granted access to massive personalized demands. Designers who are calling for manufacturing services can verify the capabilities of makers or claim personalized service demands on the Makerchain. Regulators can verify demands proposed by designers. Blockchain is synchronized with other digital twin systems (Zhang et al., 2017a) based on integration across IoT installations in the Makerchain.

Each manufacturing service matching between demander and provider is recorded as a transaction in blockchain. A block usually contains a number of transactions (*i.e.*, manufacturing service matching) in a period of time. Blockchain is the log of historical matching events and is prerequisite for sustaining trust relationships in the Makerchain. It can be acting as both a reference of trust evaluation among makers and a starting point for enhancing the efficiency of decentralized cooperation. By integrating the contextual data mining algorithm into smart contracts and decentralized applications, the Makerchain clusters makers in various temporal communities depending on their common interests and consensuses. Based on integrating a social-enable self-organizing algorithm into smart contracts and decentralized applications, the Makerchain can enhance the flexibility of manufacturing flow management for massive personalized demands.

To make the proposal clearer, we give some clarifications as follows.

Clarification 1: Smart Gateway is designed to enable blockchain nodes to access each other with seamless internetworking. It is actually a server behind a RESTful API that abstracts the actual communication between the upper-level blockchain nodes and lower-level devices through the use of dedicated drivers and standard protocols (*e.g.*, Bluetooth and Zigbee). The smart gateway

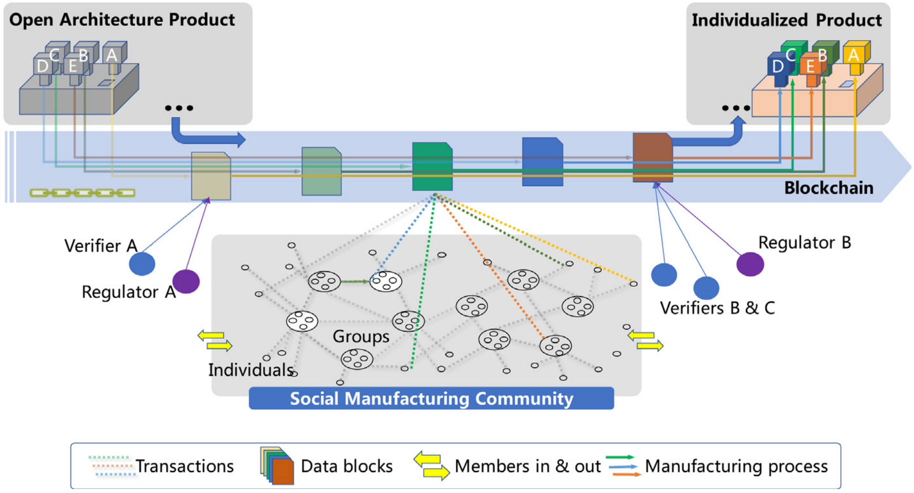


Fig. 1. Blockchain-driven Makerchain for mass personalization.

is lightweight and extensible software components embedded in devices to enable smart contracts-based interactions with all kinds of blockchain nodes.

Clarification 2: Smart Machine is defined as a machine that is equipped with the sensors/controllers needed to become conscious elements and knows its capabilities to finish a correct machining task every time in an optimal/efficient way. It can adapt itself using the context data to fill the gap between the machining demands and capabilities.

Clarification 3: Smart Service is a service with which providers can dynamically interact with demanders in an automated and personalized manner, can flexibly sense and adapt to the demanders' needs, and can be composed to form environments. It is the interactive collaboration reality resulted from the matchmaking between manufacturing demands and capabilities. It is clearly prerequisite and foundation for establishing and maintaining manufacturing network.

3.2. Blockchain model for decentralized coordination

There are two types of blockchain networks, namely, public blockchain and permissioned blockchain. Public blockchain builds computational trust on asymmetric cryptography, consensus algorithms such as Proof of Work, and special incentive mechanism. It enables users to exchange the value without knowing the basic information of the other partners. Permissioned blockchain has strict control for data access while providing efficiency and privacy of transactions. The major metrics of adopting permissioned blockchain are the tamper-resisting of data and programmable smart contract to handle dynamic process patterns. Considering the privacy protection needs in the social manufacturing paradigm, this paper utilizes the permissioned blockchain for providing a tampering-resistant decentralized database, avoiding vulnerability from crash-down or attack from centralized nodes.

3.2.1. Transaction model

The decentralized blockchain runs on multiple distributed nodes verifying the integrity of transactions in blocks across entire Makerchain network. Each block in a blockchain is a record of the recent transactions (*i.e.*, manufacturing service matching) that have taken place over the Makerchain, while a transaction includes events log of the manufacturing process being tracked. The transaction and block data model are critical to the synchronization efficiency of consensus algorithm as well as the capacity of blockchain.

Each maker with a unique identity address in the Makerchain will be given the ability to write manufacturing service events to the permissioned blockchain. Manufacturing service events recorded via smart gateways are batched up and gathered as transactions uploaded to the blockchain. The transaction data model includes following three types of information.

1) For registering of a new workpiece and updating/discontinuing of personalized demands, a smart workpiece descriptive model is built as:

$$sw_i ::= \{WID_i, WN_i, WO_i,\ WP_i,\ WD_i,\ WMT_i,\ WM_i, WF_i, WT_i, WR_i\}$$

where the properties denote identification WID_i, name WN_i, ownership WO_i, position WP_i, delivery time WD_i, manufacturing type WMT_i, material WM_i, manufacture features WF_i, form and position tolerance WT_i, surface roughness WR_i of the personalized workpiece demands proposed by designers, respectively. Specifically, the manufacturing features WF_i refer to the basic shapes and structures (*e.g.*, key slot, groove, chamfer, and thread) to be machined using some cutting tool or processing method to compose a workpiece. WM_i, WF_i, WT_i, and WR_i can be intersection and union of multiple demands, and thus these elements have multiple cardinality. For example, WT_i can be instanced by a set: $\{Coaxiality : 0.02mm,\ Circularity : 0.03mm,\ Linearity : 0.04mm\}$.

2) For registering and updating the status of a smart machine (*e.g.*, installing and crash-down of a smart machine, upgrading to the machine, service updating or discontinuation), a smart machine descriptive model is built as:

$$sm_i ::= \{MID_i, MO_i, MN_i,\ MT_i, MM_i,\ MF_i, MA_i, MR_i, OEE_i\}$$

where the elements refer to identification MID_i, ownership MO_i, name MN_i, manufacturing type MT_i, material MM_i, desired manufacture features MF_i, desired form and position accuracy MA_i, desired surface roughness MR_i, and overall equipment effectiveness OEE_i of smart machine owned by makers, respectively. For instance, the Manufacturing Type property can be divided with an optimal granularity of sub-classed to represent the desired domain for service matching.

3) Service Matching Event (SME), which is the outcome of Smart Service Autonomous Matching Contract (it will be detailed later). It denotes a series of consecutive events related to workpieces or machines. In general, a Service Matching Event between the i^{th} machine and the k^{th} workpiece can be denoted as:

$$sme_i^k ::= \left\{t_i^k,\ E_i^k,\ M_i^k,\ L_i^k,\ W_i^k,\ S_i^k\right\}.$$

where t stands for the time that event happens; E denotes physical events (*e.g.*, drilling, turning, mining, and grinding); M is to identify the machine for manufacturing the given workpiece; L identifies the location that event happens; W denotes the manufactured workpieces; and S represents the type of manufacturing service. This data model can be utilized to describe an event flow and identify the manufacturing process of products, as its personalized manufacturing features/tasks are performed one by one. All of these matching events may be coded in a JSON-like data structure and identified as transactions in the Makerchain.

3.2.2. Block model

The block model includes a series of transactions that are aggregated and validated by decentralized maker nodes. Each block contains an immutable hash of its previous block that it is directly connected with, which finally turns into a chain of blocks capturing manufacturing data that are associated with certain machines and workpieces. An assembly of all transactions, can represent a chain of manufacturing events of a personalized product via a graphical formalized state-block deduction model. The model describes the time-sensitive state and position changes of work-in-progress flows, which is introduced in our previous study and thus will not be detailed here for concise reason (Jiang and Cao, 2013). In essence, the block model comprises of multiple discrete manufacturing events, and can be denoted as follows:

$$SW_k = \left(sme_1^k, sme_2^k, \ldots, sme_i^k, \ldots, sme_n^k\right).$$

Each blockchain transaction (Tx) forming the personalized products uses the original parent Tx hash as a prefix. The structure of these transactions and event data attached to each one is illustrated in Fig. 2. The block header contains the previous block hash, Merkle root, technical data, the timestamp, and a Nonce random number for validating valid hashes of latter blocks. The number of transactions included in a single block affects the block size, which can be optimized on blockchain infrastructure.

3.3. Lifecycle digital twin model of personalized workpieces

One shortcoming in the decentralized self-organization of the Makerchain is the limited storage capacity, including both the blockchain network that runs Makerchain system and the data-tag attached on each blockchain node. To tackle the first kind of limited-capacity, smart contracts can be designed to enable the massive manufacturing data to be stored on a limited number of super nodes rather than all nodes across the entire Makerchain network, cutting-down the storage costs. To tackle the second kind of limited-capacity, most of original raw data will not be stored directly in the blockchain avoiding consume too much space and thus reduce performance of consensus algorithm. Instead, a digital twin system is built to synchronize the actual manufacturing data in a full copy manner (Liu et al., 2018). The hash of major manufacturing data that will be recorded in the blockchain, which could cut-down the storage costs and privatize the manufacturing data uploaded onto the Makerchain.

3.3.1. Abstraction of information into data entry

The data-tag (*e.g.*, QR code and RFID tag) attached on workpieces acts as a bond between cyber space and physical space for quality controlling and anti-counterfeiting. It is easily analyzed for encoding the data into the Makerchain accompanying with information of the physical workpieces. Since the storage capability of data-tag is usually limited, a formerly-proposed abbreviation schema is adopted to accommodate this limitation (Leng et al., 2018b). Through a translation algorithm, the identification of data-tag on each workpiece connects to the specific blockchain transactions on the Makerchain, and it acts as the start anchor of the workpiece's associated digital twin mapping to the physical space throughout its lifecycle (Zhao et al., 2019). The information abstracting can eliminate the synchronization process between the data-tag and blockchain.

3.3.2. Multi-view synchronization for digital twinning of workpieces

Incorporating manufacturing process data into digital twin will create significant value for continuous improving of the Makerchain, in which one challenge is to obtain the interoperability between cyber and physical space of the Makerchain. Fig. 3 illustrates a lifecycle digital twin model of personalized workpieces. A set of data entries are digitally referenced to a parent blockchain transaction, and are also twinning synchronously in the data-tag (*e.g.*, RFID tag and QR code) on workpieces (Zhang et al., 2017b). The data-tag provides a direct link to its associated digital twin data (Leng et al., 2019). These data entries forming the digital twin include not only unique chemical signature data but also data of the personalized demands, design parameters and so on. By uploading a series of transactions including workpiece data of all events, the workpiece's digital twin is therefore securitized for lifecycle quality tracking and entire anti-counterfeiting.

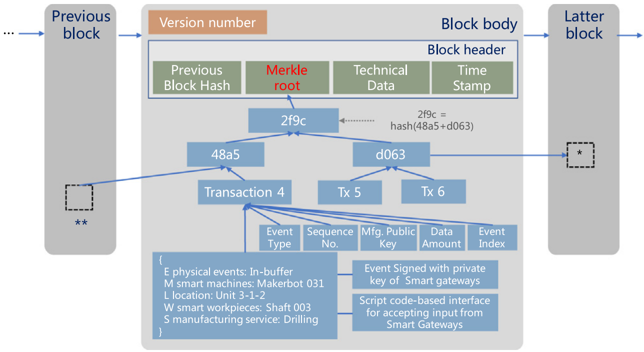


Fig. 2. Illustration of block model of manufacturing self-organization.

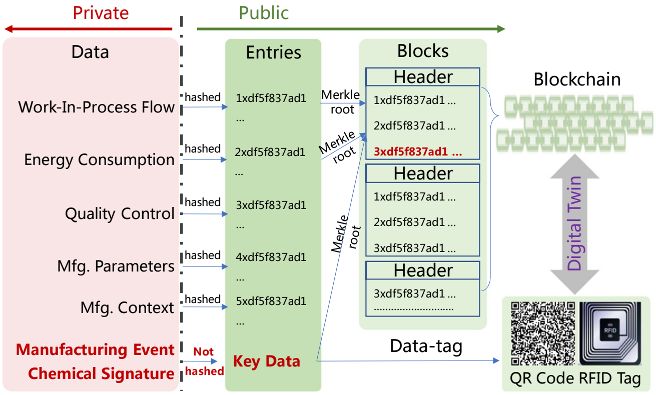


Fig. 3. Lifecycle digital twin model of personalized workpieces.

Although the blockchain is suitable for abstracting a workpiece's chain of custody and securing trust, a data synchronization with other cyber systems in the Makerchain still persists for a systematic management and analyzing purpose. On one hand, the blockchain can be acted as an enforcing proof of data obtaining from the manufacturing system that has not been tampered with, which is essential for the lifecycle quality assurance and anti-counterfeiting of product (Aurich et al., 2006). On another hand, other entity-relation database is efficient for retrieving of history transactions.

4. Chemical signature and consensus algorithm for anti-counterfeiting

The anti-counterfeiting of both cyber blockchain and physical workpiece is essential for forming trustiness among decentralized makers (Kennedy et al., 2017). Despites the consensus algorithm for guarantying data consistency among maker nodes, a need of physical or chemical verification for each workpiece in the Makerchain still persists.

4.1. Mapping chemical signature with data-tag

Each physical workpiece has a corresponding digital identification in cyber system, and this linkage between cyber system and physical system is realized by objection identification technology (*e.g.*, RFID). Although the blockchain itself can guarantee the tamper-resisting of information in the cyber system, the linkage between cyber system and physical system is vulnerable to attacks. The RFID tag attached with workpieces alone isn't solid enough to prevent replacement and other fake tags. Coupling data from embedded anti-counterfeiting physical features with blockchain network would greatly avoid the possibility of counterfeits proceeding across the Makerchain. However, since the physical features are usually elaborately designed for achieving certain function and performance goals, a chemical signature is a better choice for anti-counterfeiting as it doesn't affect the original design of workpieces while it is also easy to obtain a unique identification for each personalized workpiece (Geum and Park, 2011). The chemical signature is imbedded as one inherent property of workpiece and can be acted as a solid bond for twining and anti-counterfeiting among cyber space and physical space of the Makerchain. Therefore, this section proposes an anti-counterfeiting method by embedding engineered nanomaterials into workpiece to form a unique chemical signature/feature.

4.1.1. *Chemical signature for uniquely-characterizing workpieces*

The nanomaterials for acting as chemical signature should be not only reproducibly accompanying the physical workpiece, but also easily identified for twining the signature into blockchain. However, complicated taggants suffer from the high cost of verification, and thus are too cumbersome for makers. Carbon dots (CDs), acknowledged as a good-photostability and widely-used raw material, are selected as nanomaterials to satisfy above considerations. The key is that the embedded CDs-based taggant can provide a highly-stable fluorescence color/emission profile forming the chemical signature.

Fig. 4 illustrates the workflow of incorporating CDs as a chemical signature for uniquely-characterizing workpieces. Firstly, the CDs are prepared by microwave-assisted decomposition of urea and citric acid. The obtained CDs-based taggants are homogenously embedded into the original material of workpiece to form composite thermoplastic filaments (or powdered metals). Secondly, the CDs-based tagged composite material may be directly manufactured into products via 3D printer (or electrochemical machine). Both methods are low-cost and suitable to mass personalization. Each maker could design a unique feature of chemical signature by compositing different type and quantity of taggants. Thirdly, the tagged composite material can be used to make a QR code on a workpiece during its manufacturing process, which is then linked to the corresponding transactions on the Makerchain for twining the workpiece's physical space throughout its lifecycle activities. Finally, by various handheld techniques such as UV-light, makers can validate the fluorescence color feature against the data embedded in the blockchain transactions. Further details on the quantification of these fluorescent emission signatures produced with the CDs-based taggants will be omitted here for concise reason.

4.1.2. *Incorporating chemical signature data into blockchain*

Twinning chemical signature data into both cyber blockchain and physical manufactured products is a critical for anti-counterfeiting (Kennedy et al., 2017). The robust fluorescence emission data can be encoded to aid in the measurement when downstream makers in the Makerchain are verifying the workpiece.

To avoid counterfeiting the fluorescence feature of a particular workpiece, emission data captured at multiple excitation could be realized by rigorously controlling of the acquisition setup parameters and compared with a benchmark database, which is also stored in tamper-resisting blockchain. Therefore, a decentralized application should be developed to identify the fluorescence emission property. For instance, a workpiece composed of (90:10)-PLA/CDs composite material will display a unique fluorescence color under 420 nm excitation. A decentralized application can be used for capturing color via camera. The captured color is then converted to the RGB format, in which the value can be used to act as the chemical signature value, and thus can distinguish the authenticity and integrity of this workpiece. Factors including the quality of the camera and the lightness can be excluded by extracting CIELAB information (a device-independent color model in which the lightness will be excluded from the color components) from the RGB format.

However, the converted color information in RGB format may be still unreliable due to inconsistence and un-accuracy in manufacturing process of composite material. Therefore, a tolerance technology is integrated to allow a relatively subtle deviation of fluorescent emission. To further increase the difficulty of replicating the fluorescent emission characteristics of a specific workpiece, emission profile captured at multiple excitation wavelengths can be also compared to a reference system.

4.2. *Customized XFT consensus algorithm for data consistency*

Due to both the subjective selfish tendencies of makers and absence of cyber-level interconnection, the information asymmetry is widespread in social manufacturing paradigm. Manufacturing service providers cannot grasp personalized demands of designers who are in turn not clear providers' capabilities and cost information yet. In this case, the collaboration efficiency of the manufacturing community may decline, and even the aggregation of community may be disintegrated. It is difficult to reduce the influences caused by bilateral asymmetric information in the decision-making process and interactions, in which the decentralized consensus algorithm can provide a solution.

Consensus algorithms could ensure consistency of manufacturing data among decentralized nodes on the Makerchain. The proposed Makerchain utilizes a permissioned-type

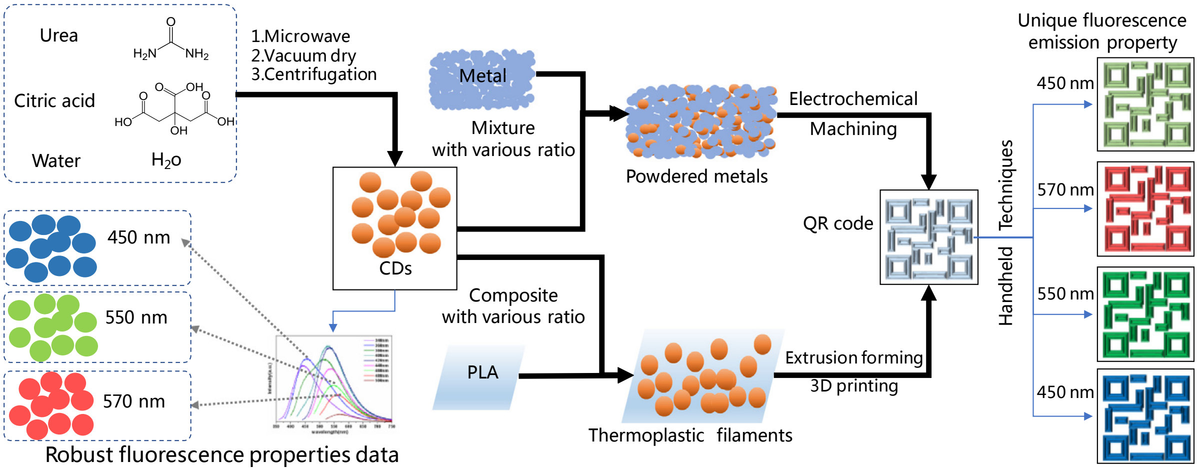


Fig. 4. Illustration of CDs as a chemical signature for uniquely-characterizing workpieces.

blockchain, which runs on a manufacturing community with IoT-based governance infrastructure that guarantees a certain level of trust. Verifying data is realized by arbitrary or assigned node on the decentralized Makerchain. The permissioned Makerchain will secure the interactions among makers that have a common goal but may not coordinate well with each other. Based on the identities of the makers, the Makerchain can utilize Crash Fault Tolerant (CFT) or Byzantine Fault Tolerant (BFT) consensus algorithms that do not need costly mining (*e.g.*, PoW). We utilize cross fault tolerance (*i.e.*, XFT) (Liu et al., 2015) to the deterministic state-machine replication in the Makerchain. An XFT protocol tolerates not only crash faults but also Byzantine faults with network asynchrony, provided the number of faulty and partitioned machines is within a pre-specified threshold. Therefore, the XFT can yield stronger resilience than CFT with the same cost of resource.

Let us model a Makerchain system containing a set of n maker nodes (*i.e.*, replicas) and a separate set C of client machines. $t_c(s)$ denotes the number of crash-faulty nodes (*i.e.*, a node stops all computing and communication). $t_{nc}(s)$ represents the number of non-crash-faulty nodes (*i.e.*, a node acts arbitrarily while cannot break cryptographic primitives). $t_p(s)$ denotes the number of correct but partitioned nodes (*i.e.*, delay is larger than a pre-specified threshold). XFT is formalized by a special anarchy if $t_{nc}(s) > 0$ & $t_c(s) + t_{nc}(s) + t_p(s) > t$, where t is the pre-specified threshold of replica faults (Liu et al., 2015). Protocol that guarantees safety in all execution scenarios in which the system is never in anarchy can be defined as XFT algorithm.

We proposed a kind of Customized XFT (CXFT) protocol on the implementation of the Makerchain, which guarantees liveness when a majority of nodes is correct and synchronous. The CXFT is developed on unique proposer-based multi-Paxos with final combined consistency $(n-1)/2$ and availability $(n-1)/2$. It consists of three major components including a common-case protocol, a novel view change protocol, and a fault detection mechanism (Liu et al., 2015). We combine the IoT governance infrastructure-based Makerchain scenario to build a self-adaptive ecology of CXFT in following aspects:

- Online addition/deletion of nodes of multiple roles and rapid transferring of leadership nodes to other nodes with primary election. Based on the weighting selection, users can specify the weight of each node, and only when the high-weight nodes are all unavailable, the low-weight nodes will be activated.
- Customization of node character. Besides the fully function (*e.g.*, proposer, accepter, and learner) of each node in implementation, there are other ways of combination of functions for each node since we do not need all the nodes to possess all the functions in some cases. Through the customized combination of node roles, we can develop a lot of customized function nodes, which saves costs and enriches functions.
- Delay-aware topology self-organizing. During steady-state operation, CXFT will perceive the network delay of each node and form a cascade topology to effectively reduce the load of the primary node and the bandwidth usage of the long transmission link. When the node is abnormal, the topology is automatically reorganized to ensure the operation of the peer among the surviving nodes.

5. Smart contract tree for self-organizing process in makerchain

The smart contract (*i.e.*, a Turing-complete intelligent implementation of contract) is critical to mediate the manufacturing service relationships and interactions among makers. Careful attention must be payed to the design and coding of smart contracts because they are inherently immutable. In the Makerchain, a tree model of smart contracts is proposed for makers to inherit. As shown in Fig. 5, the so-called smart contract tree is a hybrid reference model that majorly includes four main standard smart contracts that act as the interaction bridge between manufacturing service demanders and providers.

Rational of four standard smart contracts will be detailed in following four sub-section, respectively. Communication between contracts is constrained within a specified set. It will make the relationships among contracts become clear and predictable. Any smart contracts of different personalized product in the Makerchain can be inherited from this reference smart contract tree with some customizing of formalized parameters, generation rule, and initiation mechanism. It will greatly prevent the possibility of crash/errors as well as implementing complexity. Once a personalized workpiece order confirms and launches, all smart contracts of manufacturing services will be triggered and proactively self-organized according to the reference paradigm. The smart contracts will be interconnected with a decentralized application to twining manufacturing data from cyber-physical systems (Zhang et al., 2018). Based on the underlying interface and protocols in decentralized Makerchain network, each smart contract can divide blockchain to increase efficiency of consensus.

5.1. Smart context managing & mining contract (SCMMC)

Based on decentralized consensus algorithm, the SCMMC can access to a high-quality and unified context data among makers in the mass personalization paradigm. The SCMMC perceives the interaction and operation context for mining personalized manufacturing service demands and relationships (Leng and Jiang, 2016). The captured personalized demands and relationships are managed by following smart contracts for furtherly grouping and coordinating decentralized makers in a spontaneous community to co-create on-demand manufacturing services.

A formerly-proposed two-step contextual mining algorithm is integrated in SCMMC for capturing of personalized demands (Leng and Jiang, 2017). Standard policies about events are coded into the SCMMC for regulating operation of addition and modification. These events are broadcast to all maker nodes on the Makerchain network for validation. The Makerchain can track performance of the potential makers and then validate the provenance of historical data. Particularly, the SCMMC mediates between private entity-relation database and blockchain to secure information transferring within trustiness boundary.

5.2. Smart optimal task composition contract (SOTCC)

After captured mass personalized demands, the SOTCC is subsequently activated. The requirement of optimally compositing demands results from both the limited capabilities/resources and the loading of makers. Considering the variability of personalized demands in both spatial and temporal dimensions, which demands to be hosted have to be judiciously analyzed and decided to maximize utility of community. On another hand, an appropriate loading degree of task for each maker is supposed to be a balance between the number and the size of tasks (Leng et al., 2019).

The SOTCC is established for clustering and compositing personalized demands into tasks in an optimal granularity, and the difficulty is to achieve a trade-off between information entropy and minimal similarity in all granules. The influence of matching degree between demands and capabilities should be also taken into consideration. By integrating formerly-proposed granular

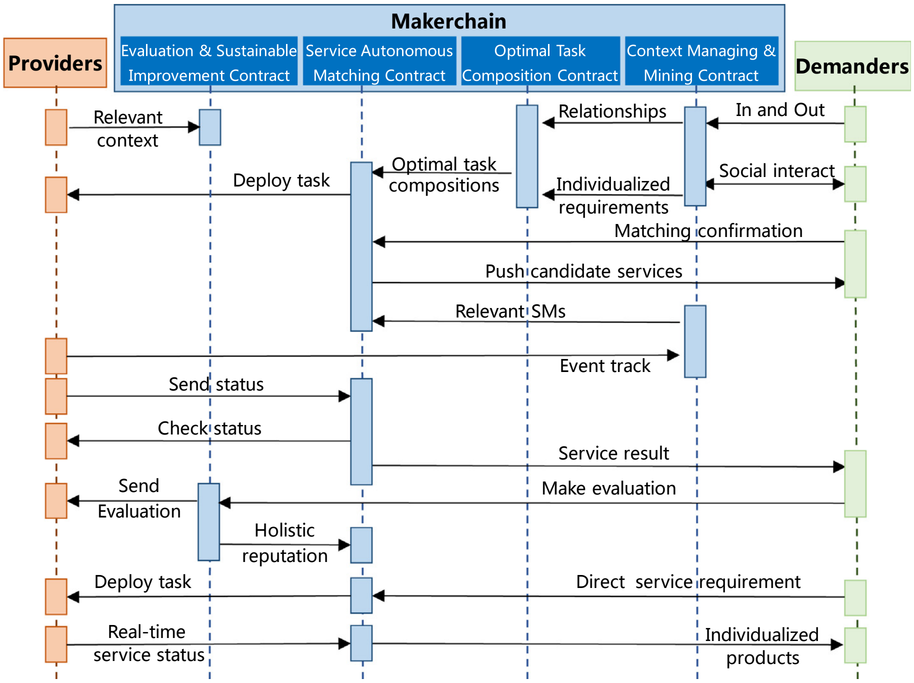


Fig. 5. Interaction flow among smart contract tree and smart entities.

computing algorithm (Leng and Jiang, 2017), the optimal granules can be obtained in SOTCC, and thereby help narrow down the scope of makers' self-organizing adjustments to a reasonable granularity of demands.

5.3. Smart Service Autonomous Matching Contract (SSAMC)

After composing demands into tasks in an optimal granularity, how to coordinate these tasks among makers in the Makerchain is another issue. Conventional holistic planning or scheduling strategies often don't work effectively when organizing tasks in a decentralized and loosely-coupled network (Leng and Jiang, 2019). The SSAMC for social manufacturing paradigm characterizes the current collaboration activities via service matching relationship, which is similar to the logic of demand-supply matching in conventional collaborations (Leng et al., 2018a).

A decentralized self-organizing algorithm is integrated to dynamically organize suitable makers to satisfy demanders' personalized goal (Leng et al., 2018b). The process is designed as follows: 1) clustering makers for service provisioning, 2) discovering suitable makers to meet personalized demands, in which a maximal-similarity preferred matching algorithm is adopted in this step. It includes subsumption matching, similar matching, and constraint reasoning. The subsumption matching is of high computational efficiency for the properties with strict structure. The similar matching is to evaluate similar properties that are difficult for modeling in a strict and complete manner. We adopt a hybrid similar matching algorithm of three basic similarities, namely, semantic distance, semantic coincide degree, and level difference. The constraint reasoning is to sufficiently filter the rigid properties. Finally, the most suitable maker will be selected as its performer.

5.4. Smart evaluation & sustainable improvement contract (SESIC)

When the selected maker submits a signal of finished-task to the SSAMC by itself, the SESIC is activated. The trail of service matching events can help establish reputation and impute trust among makers. To realize a sustainable self-organizing paradigm in the Makerchain, the makers will receive an evaluation from the designer/demander when each manufacturing service is finished. A dynamic reputation-based trust evaluation is imbedded in the SESIC to periodically identify reputed makers, and thus achieve a sustainable self-organizing trend. Based on the retrieval of historical service events related to the makers with regards to its manufacturing history, the Makerchain will provide incentives for each maker acting as intermediary node to coordinate service tasks.

The self-organizing process of manufacturing service is fulfilled by four standard smart contracts, which cannot be recorded in the transactions of data block model, since it requires a hug storage space and will lead of low-efficiency of consensus algorithm. This matchmaking result (*i.e.*, sme_i^k) is broadcast to all maker nodes on the Makerchain for validation. Therefore, the potential manufacturing service demander's blockchain agent can verify the authenticity of the transaction data and then track historical performance of the service provider. Sharing of service matching results will increase the reputation of the makers and improves the odds of service matchmaking.

Other contracts such as Smart Registering & Management Contract are also included in the contract tree, but not detailed here for the concise reason. Through various smart contracts, makers are connected to the upstream and downstream of product manufacturing community, and a digital twin for each products' life-cycle activities is formed in the virtual world of the Makerchain.

6. An example of decentralized application

This section presented a decentralized application prototype to demonstrate the feasibility of connecting maker nodes on a social manufacturing network.

6.1. System rationale

As shown in Fig. 6, the infrastructures of the Makerchain include manufacturing section and networking section (*e.g.*, smart gateways). The blockchain will provide interface address of RPC and HTTP for cyber-physical systems of machines, and users can remotely manipulate the blockchain for realizing blockchain-driven smart contracts and decentralized applications (DApps). Other database and user interface applications can be developed as plug-n-play features via RPC calling of relevant smart contracts on blockchain. The smart gateway is hosted to enable machine-to-machine communication built on a key-value database (Mishra et al., 2018). The DApps as well as smart contracts enforce cryptographic proofs that the manufacturing data obtaining from the digital twin model has not been tampered with. The blockchain serves as an indexing server for tracking the transactions on the Makerchain. Finally, a decentralized social manufacturing paradigm is enabled, which is different from conventional hierarchical and centralized manufacturing paradigm.

It must be noted that the Makerchain does not include detailed in-process manufacturing data related to the personalized workpiece. Instead, the Makerchain will only include link to the manufacturing data gathered within the makers' manufacturing execution system. To address the lack of privacy and confidentiality for self-organizing of manufacturing services, the Makerchain provides a means to share the decryption keys, and participants can hash or encrypt the data (*e.g.*, SHA 256, AES256) before calling smart contracts. Unauthorized participants will have a hash of the private data on the channel ledger as evidence of the transaction data. Hashes of the private data go through the blockchain to keep it confidential from other nodes. Also, for further privacy, participants can restrict the input data to smart contracts to the specified set of partners and enable confidentiality through a channel architecture. Specific adaptors must be written to allow outside systems interact with the smart contracts on the Makerchain. Since the smart contract are self-executing, the smart gateway can provide the real-time data for enabling the computing of smart contracts.

6.2. *Case study*

This paper takes the open source RepRap 3D printers project (*i.e.*, a general-purpose small-size rapid prototyping and self-replicating manufacturing machine) as a case study of decentralized social manufacturing of open architecture products. Makers can personalize RepRap printer according to their needs. Communities offering RepRap 3D printing and other manufacturing services are already forming online. We present below an example of decentralized social manufacturing of personalized RepRap 3D printer, as shown in Fig. 7. A Makerchain network comprising 6 super nodes and multiple replicas is set up acting as various makers of the blockchain. A maker node may have multiple machines providing the manufacturing service to serve the demanders and designers. Each maker with a unique smart gateway will be enable to directly upload critical manufacturing events to the Makerchain.

The makers join community in the Makerchain to co-design the printer, and also co-create a library of personalized modules. For instances, manufacturing service providers in Chengdu can get the digital drawings of personalized product from designers in Guangzhou and then print it locally, which will reduce warehousing of final products, cut logistics cost, and also get product of high-quality. The manufacturing process of a personalized RepRap printer in the Makerchain majorly includes following five steps:

Step 1: to supply a kind of product or manufacturing service, a user can choose a list of smart contract paradigm. He filled it with basic information including his signature, product instructions, personalized demands, the delivery date, and so on. Once received the order, the smart contracts will be automatically activated in the Makerchain.

Step 2: the goal is to enable the self-organizing of makers. Firstly, the SOTCC will composite and aggregate the personalized demands into serval tasks in an optimal granularity. Secondly, every maker node on the Makerchain network can send service bids to the SSAMC without knowing the source of the new-coming tasks. Thirdly, the SCMMC will utilize the maximal-sustainability-preferred strategy to search suitable makers which can meet the personalized tasks on quality and time. Finally, once the makers are matched into tasks, the Makerchain will push status updates to demanders for adaptive decisions in the self-organizing progress.

Step 3: workpieces are manufactured with data written directly into the physical QR code or RFID data-tag. A digital twin for one part in the personalized RepRap printer referred as "0103A" is chosen as example. The blockchain records separate Tx hashes including not only the carbon dots-based fluorescence color signature but also current status, machining processes, personalized demands, and process tracking information, as shown in Fig. 7. The Tx hash for the digital twin of personalized part can be easily located via a block explorer. User can search

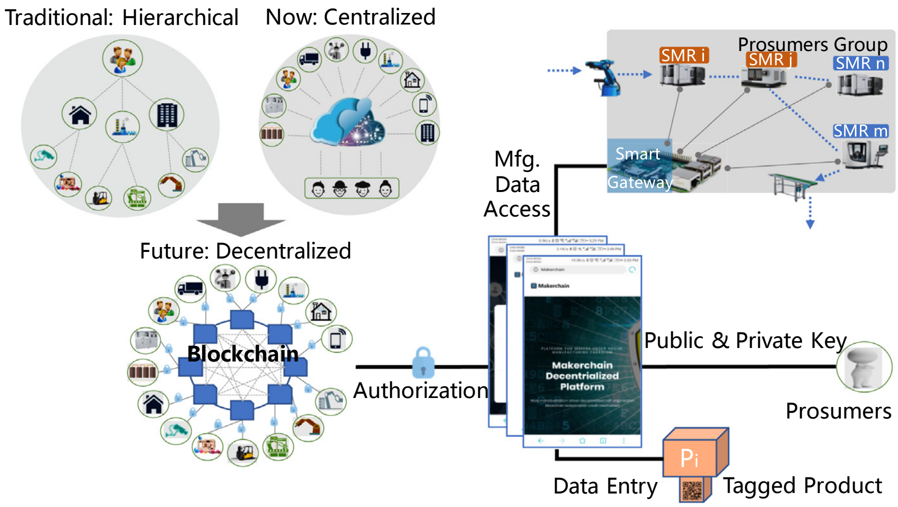
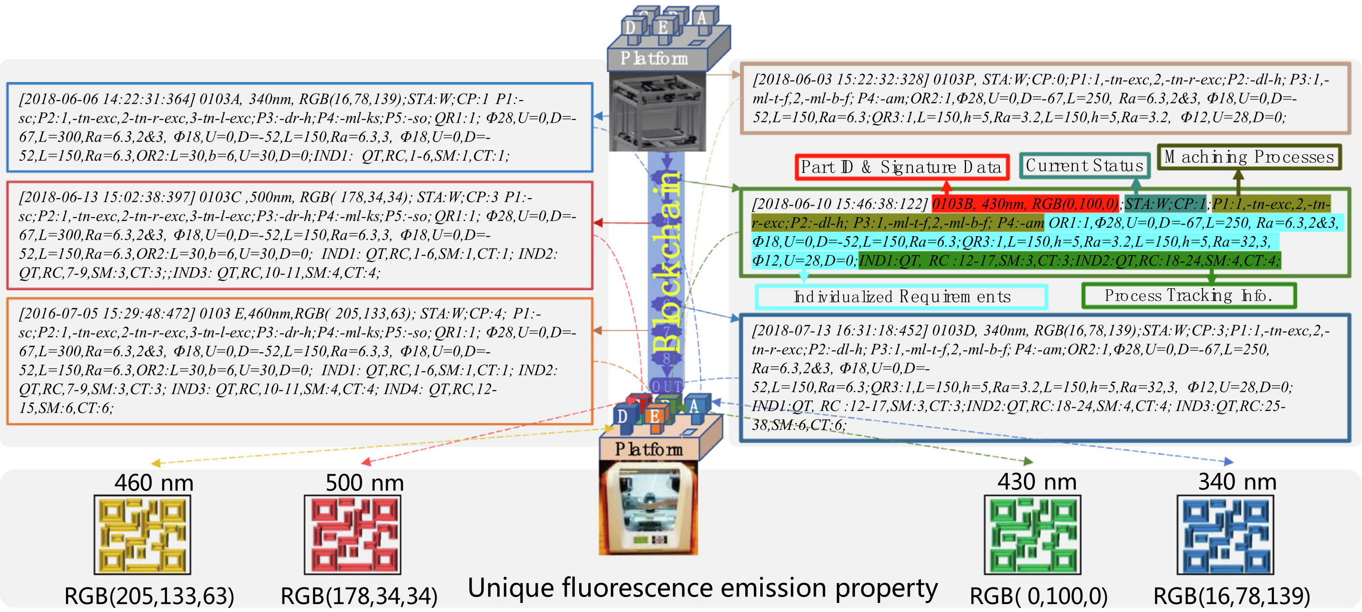


Fig. 6. Elements and rationale of porotype Makerchain system.



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[2018-06-06 14:22:31:364] 0103A, 340nm, RGB(16,78,139);STA:W;CP:1 P1:-sc;P2:1,-tn-exc,2-tn-r-exc,3-tn-l-exc;P3:-dr-h;P4:-ml-ks;P5:-so; QR1:1; Φ28,U=0,D=-67,L=300,Ra=6.3,2&3, Φ18,U=0,D=-52,L=150,Ra=6.3,3, Φ18,U=0,D=-52,L=150,Ra=6.3,OR2:L=30,b=6,U=30,D=0;IND1: QT,RC,1-6,SM:1,CT:1;

[2018-06-13 15:02:38:397] 0103C ,500nm, RGB( 178,34,34); STA:W;CP:3 P1:-sc;P2:1,-tn-exc,2-tn-r-exc,3-tn-l-exc;P3:-dr-h;P4:-ml-ks;P5:-so; QR1:1; Φ28,U=0,D=-67,L=300,Ra=6.3,2&3, Φ18,U=0,D=-52,L=150,Ra=6.3,3, Φ18,U=0,D=-52,L=150,Ra=6.3,OR2:L=30,b=6,U=30,D=0; IND1: QT,RC,1-6,SM:1,CT:1; IND2: QT,RC,7-9,SM:3,CT:3;;IND3: QT,RC,10-11,SM:4,CT:4;

[2016-07-05 15:29:48:472] 0103 E,460nm,RGB( 205,133,63); STA:W;CP:4; P1:-sc;P2:1,-tn-exc,2-tn-r-exc,3-tn-l-exc;P3:-dr-h;P4:-ml-ks;P5:-so; QR1:1; Φ28,U=0,D=-67,L=300,Ra=6.3,2&3, Φ18,U=0,D=-52,L=150,Ra=6.3,3, Φ18,U=0,D=-52,L=150,Ra=6.3,OR2:L=30,b=6,U=30,D=0; IND1: QT,RC,1-6,SM:1,CT:1; IND2: QT,RC,7-9,SM:3,CT:3; IND3: QT,RC,10-11,SM:4,CT:4; IND4: QT,RC,12-15,SM:6,CT:6;

[2018-06-03 15:22:32:328] 0103P, STA:W;CP:0;P1:1,-tn-exc,2,-tn-r-exc;P2:-dl-h; P3:1,-ml-t-f,2,-ml-b-f; P4:-am;OR2:1,Φ28,U=0,D=-67,L=250, Ra=6.3,2&3, Φ18,U=0,D=-52,L=150,Ra=6.3;QR3:1,L=150,h=5,Ra=3.2,L=150,h=5,Ra=3.2, Φ12,U=28,D=0;

[2018-06-10 15:46:38:122] 0103B, 430nm, RGB(0,100,0);STA:W;CP:1;P1:1,-tn-exc,2,-tn-r-exc;P2:-dl-h; P3:1,-ml-t-f,2,-ml-b-f; P4:-am OR1:1,Φ28,U=0,D=-67,L=250, Ra=6.3,2&3, Φ18,U=0,D=-52,L=150,Ra=6.3;QR3:1,L=150,h=5,Ra=3.2,L=150,h=5,Ra=32,3, Φ12,U=28,D=0;IND1:QT, RC :12-17,SM:3,CT:3;IND2:QT,RC:18-24,SM:4,CT:4;

[2018-07-13 16:31:18:452] 0103D, 340nm, RGB(16,78,139);STA:W;CP:3;P1:1,-tn-exc,2,-tn-r-exc;P2:-dl-h; P3:1,-ml-t-f,2,-ml-b-f; P4:-am;OR2:1,Φ28,U=0,D=-67,L=250, Ra=6.3,2&3, Φ18,U=0,D=-52,L=150,Ra=6.3;QR3:1,L=150,h=5,Ra=3.2,L=150,h=5,Ra=32,3, Φ12,U=28,D=0; IND1:QT, RC :12-17,SM:3,CT:3;IND2:QT,RC:18-24,SM:4,CT:4; IND3:QT,RC:25-38,SM:6,CT:6;
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Fig. 7. The custody chain of products' manufacturing personalized process.

for the QR code's Tx hash as a prefix to yield its virtual part twining the physical one. Within the blockchain transactions, one data entry will capture the finished process and be uploaded for associating its digital twin: "*[2018-06-06 14:22:31:364] 0103A*, 340 nm, *RGB (16,78,139); STA: W; CP: 1; P1: -sc; P2: 1, -tn-exc, 2-tn-r-exc, 3-tn-l-exc; P3: -dr-h; P4: -ml-ks; P5: -so; QR1: 1; Φ28, U=0, D=-67, L=300, Ra=6.3* …"

Step 4: after finishing of the personalized manufacturing services, user can use a handheld UV light-based standard QR code reader to verify the finished product at appropriate wavelength, and a unique RGB color of the QR code will illuminate the integrity throughout its lifecycle. The obtained link to its parent Tx hash is automated to verify origination of finished products.

Step 5: the SESIC contract will compare key performance metrics among related makers to impute continuous improvements, and the makers can learn practices in the Makerchain network. The most reputed maker will be selected as performer of next-coming similar tasks with larger possibility.

6.3. Discussions

To illustrate the advantage of decentralized social manufacturing paradigm compared to conventional hierarchical and centralized manufacturing paradigm, a simulation for three product-oriented manufacturing networks with different scale, namely, Gravure Printing Machine (GPM), Flexographic Printing Machine (FPM), and Coating Printing Machine (CPM), are conducted. Data shown in Fig. 8 are collected from a National High-New Technology Zone of China. Network metrics of three networks under conventional paradigm have been discussed in our former study (Leng and Jiang, 2018).

Using a Monte Carlo simulation method, we make comparison regarding the characteristics of network metrics under the Original and Makerchain (MC) paradigm, as shown in Table 1. Network metrics (*i.e.*, Density, Disparity, Centralization, Degree, Transitivity, and Clustering Coefficient) are compared in normalized form, which allows us to compare them across three different networks. Implications from original metrics of three network have been discussed in our former study (Leng and Jiang, 2018). This section will concentrate on the contrast between original and decentralized social manufacturing paradigm simulated based on the Makerchain. The Network Scale and Disparity remain unchanged in both paradigms.

The Density obtained in MC is smaller than that it in Original network, evidenced by the smaller metrics of 0.0107, 0.0045 and 0.0013. The smaller density implies that makers in MC focus on catering to the demanders' needs and are concentrated on their core competence, which consequently leads to a more effective network for the collaboration. With respect to Centralization, the metrics obtained in MC is lower than that in Original network. The relatively lower centralization implies that makers in MC provide more efficiency and higher level of flexibility and responsiveness as they pay less management attention on disruptions. The Degree (*i.e.*, Connectivity) in MC is smaller than that it in Original network, evidenced by the smaller metrics of 2.282, 2.290 and 2.600. It implies that makers in original network have more outsourcing/service relationships and thus produce a larger scope of influences on other maker nodes. Meanwhile, makers in Original network are forced to coordinate conflicting interests or decisions with other maker nodes. The clustering coefficients (*i.e.*, Transitivity) of three networks in MC are larger than that in Original network. This phenomenon implies that the Original networks are likely organized in a hierarchical structure and have less overlapping and clustering. The larger the transitivity, the maker is more likely correlated with other makers on the collaboration. In general, MC is superior in the relational capability to interact among makers and transfer with positive effects on their competencies, and the makers are concentrated more on the core competence and become more specialized in a specific area. On the contrary, blockchain-based decentralization gives every individual the opportunity to be the center of the network. Any node can be a hub at one stage, but it does not have mandatory central control ability.

Social manufacturing is a kind of distributed and open mode of manufacturing (Ding et al., 2018). Makers can directly adjust to the high-margin stage of product lifecycle, which would greatly improve the efficiency of decentralized cooperation and promote the rational allocation of resources. Rich data interfaces for the

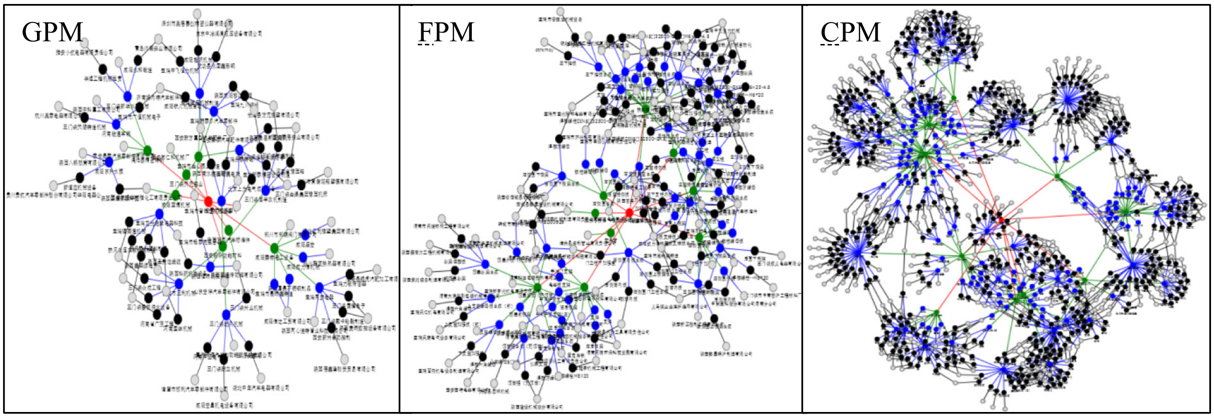

Fig. 8. Three Printing Machine product-oriented manufacturing network (Leng and Jiang, 2018).

Table 1
Network metrics of three network under Original and Makerchain paradigm.

Metrics	GPM		FPM		CPM	
	Original	MC	Original	MC	Original	MC
Network Scale	108	108	255	255	1002	1002
Disparity	1.144	1.144	1.323	1.323	1.424	1.424
Density	0.0112	0.0107	0.0049	0.0045	0.0015	0.0013
Centralization	0.0561	0.0478	0.0236	0.0203	0.0060	0.0049
Degree	2.389	2.282	2.494	2.290	3.000	2.600
Clustering Coefficient	0.007	0.009	0.004	0.005	0.009	0.012

blockchain can be developed for supporting decision-making and network adaptive-optimizing using big data analytics (Xu et al., 2019).

However, sharing of manufacturing data can be a sensitive topic for many makers and manufacturers. Given enough time and computational resource, the encrypted data sitting on the blockchain could be broken. To avoid any node viciousness tracking and disturbing transactions on the open information in blockchain, it is necessary to explore privacy protection algorithms such as “zero-knowledge proofs” (ZKP). We are working on ZKP to improve upon privacy and confidentiality capabilities in the future. On another hand, due to both security concerns and lack of infrastructure, a low-level network connectivity of the machines prevents the wider-scale adoption of blockchain to manufacturing network (Jiang et al., 2016). It is of great significance in developing IoT (Zhang et al., 2016) toward a more advanced stage of Blockchains of Things.

7. Conclusions

This paper proposed a Makerchain model of utilizing blockchain-driven smart contracts for decentralized self-organizing in social manufacturing of product architecture products. Blockchain serves as a tampering-resistant decentralized database updated over time for avoiding vulnerability from centralized nodes in establishing trust among makers. The proposed Makerchain incorporates a low-cost and easy-implementing carbon dots-based chemical signature twinning with physical QR code to improve workpiece lifecycle security and prevent counterfeits. The measured fluorescence emission data of chemical signature is amended for ensuring trust. A smart contract tree for mass personalization is proposed based on integrating of our formerly-proposed context mining, granular computing, self-organized matching, and sustainable evaluation algorithms. It is a new crowd intelligence way to achieve mass personalization paradigm in the manufacturing area.

Integrating blockchain into social manufacturing will create value for the industrial economy transformation and upgrading. However, there are some limitations to be addressed in future. The mass personalization as well as decentralized social manufacturing paradigm are not yet practiced on a large scale. Consequently, more empirical case studies should be conducted to grasp the organizing rational and to gain a better understanding of the operation mechanism of blockchain in social manufacturing paradigm. There is also much work to be done to combine blockchain principles, cyber-physical systems, and other value-adding techniques into the social manufacturing domain.

Declaration of conflicting interests

The authors declare that they have no conflict of interest.

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