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Industrial blockchain based framework for product lifecycle management in industry 4.0

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ABSTRACT

Product lifecycle management (PLM) aims to seamlessly manage all products and information and knowledge generated throughout the product lifecycle for achieving business competitiveness. Conventionally, PLM is implemented based on standalone and centralized systems provided by software vendors. The information of PLM is hardly to be integrated and shared among the cooperating parties. It is difficult to meet the requirements of the openness, interoperability and decentralization of the Industry 4.0 era. To address these challenges, this paper proposed an industrial blockchain-based PLM framework to facilitate the data exchange and service sharing in the product lifecycle. Firstly, we proposed the concept of industrial blockchain as the use of blockchain technology in the industry with the integration of IoT, M2M, and efficient consensus algorithms. It provided an open but secured information storage and exchange platform for the multiple stakeholders to achieve the openness, interoperability and decentralization in era of industry 4.0. Secondly, we proposed and developed customized blockchain information service to fulfill the connection between a single node with the blockchain network. As a middleware, it can not only process the multi-source and heterogeneous data from varied stages in the product lifecycle, but also broadcast the processed data to the blockchain network. Moreover, smart contract is used to automate the alert services in the product lifecycles. Finally, we illustrated the blockchain-based application between the cooperating partners in four emerging product lifecycle stages, including co-design and co-creation, quick and accurate tracking and tracing, proactive maintenance, and regulated recycling. A simulation experiment demonstrated the effectiveness and efficiency of the proposed framework. The results showed that the proposed framework is scalable and efficient, and hence it is feasible to be adopted in industry. With the successful development of the proposed platform, it is promising to provide an effective PLM for improving interoperability and cooperation between stakeholders in the entire product lifecycle.

1. Introduction

Product Lifecycle Management (PLM) is the business activity of managing a company's products all the way from the very first product idea all the way through until it is retired and disposed of [1]. It aims to drive innovation, accelerate product development time, reduce costs, improve quality, visualize product information, and shorten the communication gaps between the cooperating parties [2]. Originally, PLM is mainly used to support the local data and information integration and management in the stage of product design and development, such as assisting product designers to access the information generated from computer aided designing (CAD), computer aided manufacturing (CAM), computer aided engineering (CAE), etc. Enabled by the development of Internet and information technologies, it expands the range to involve stakeholders to collaborate throughout the entire product lifecycle. It involves a series of stages of product lifecycle, including research and development, production, distribution, maintenance, customer service, and recycling. PLM becomes a strategical solution to improve the product competitiveness of the enterprise [3].

Industry 4.0 (I4.0) is commonly referred to the fourth industrial revolution by incorporating various emerging technologies, including cyber-physical systems, Internet of things (IoT), artificial intelligence (AI), and cloud computing for developing open, secured, and smart factories. However, conventional PLM approach is insufficient to

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support I4.0. Firstly, most of the existing approaches are developed based on a centralized framework provided by third party software vendors. For example, some researchers have proposed cloud-based PLM systems in industry [4]. However, companies have the concerns about key innovation leakage and loss, which leads to the openness of information and services remain superficial and limited. Intellectual property and security issues are the main concerns of the companies [5]. Secondly, there is a large amount of disperse product information along the distributed lifecycle, such as the iterative drawing files, updated bill of materials, real-time quality feedback and various maintenance demands, etc. The conventional centralized approach is mainly developed for in-house use. However, the product information chain along the lifecycle spans enterprise boundaries. Therefore, it is hard to access, process, and analyze such information across enterprises. Likewise, I4.0 requires an integration of value chain organization and management across the product lifecycle [6]. Thirdly, traditional PLM systems lack an effective mechanism for knowledge and services exchange and sharing among the stakeholders in the product lifecycle. The existing mechanism is based on time consuming communication between different stakeholders. It is time and labor intensive. This is because the security issues. Besides, the main reason for this situation is due to the absence of an incentive mechanism for the enterprise to exchange and share, the enterprise cannot attain too much profit from the sharing of knowledge. However, I4.0 requires a decentralized decision-making to utilize local and global information at the same time for better decision-making and increasing productivity [7]. To conclude, it needs an open and yet secured, interconnected and decentralized environment for information integration and exchange and decision-making among the products, factories, business network and customers from the different stages of product lifecycle.

In order to solve the above challenges, an industrial blockchain-based PLM platform is proposed. This approach incorporates industrial blockchain, smart contract and IoT technologies. Blockchain is a revolutionary technology in finance world, which has the advantage of high security, irreversibility, distributivity, transparency and accuracy [8]. Beyond the finance application, it has also showed great potential in industry fields. Mattila et al. proposed an industrial blockchain platform for autonomous machine-to-machine (M2 M) transactions [9]. To meet the various industrial standards, Li et al. highlighted a novel blockchain architecture “satellite chain” that runs different consensus protocols [10]. Li et al. have studied the consortium blockchain widely in Industrial IoT. [11]. Summing up, the industrial blockchain can be broadly defined as the use of blockchain technology in the industry with the integration of IoT, M2 M, and efficient decentralized consensus algorithms to satisfy the demand of security, openness and decentralization. In addition, we use smart contracts to facilitate transaction executions and alert services in the product lifecycles. IoT technologies to collect and monitor the real-time data from the product lifecycle.

The contribution of this paper is summarized as follows: (1) The proposed industrial blockchain-based platform provides an open but secured, interconnective and decentralized environment in the era of I4.0. It enables a cooperative environment for stakeholder in PLM to conduct information exchange and sharing among the products, factories, business network and customers. (2) The proposed customized blockchain information service (BIS) integrates disperse information along the product lifecycle. This not only helps an enterprise to better re-utilize the inner resources, but also allows the enterprise to create a value chain to study and analyze the cross-enterprise product information. (3) The proposed platform provides a smart contract enabled transactions and alert services in the product lifecycle. It helps the enterprise to provide instant decision-making and support. The procedure in smart contract is executed in blockchain automatically rather than manual operation, which enhance the effectiveness and efficiency of transactions and operations in PLM. Therefore, it reduces the time and labor costs. (4) Four blockchain-based key services in the PLM is illustrated, including co-design and co-creation service, quick and accurate tracking and tracing (QAT^2) service, proactive maintenance and regulated recycling service. The key services show that it can have a connection with existing enterprise function model such as ERP, M2 M, etc.

The rest of this paper is organized as follows. Section 2 provides a review of PLM and blockchain. The architecture of the proposed industrial blockchain-based PLM is presented in Section 3. Section 4 describes the mechanism of four key services, including co-design and co-creation service, QAT^2 service, proactive maintenance service, and regulated recycling service. In Section 5, the experimental simulation and evaluation is presented to illustrate the performance of the proposed framework, including the qualitative and quantitative comparisons, evaluation of the latency and the throughput during new block generation. Finally, conclusion and further research are summarized in Section 6.

2. Literature review

2.1. Product lifecycle management

The PLM concept can be broadly defined as a product centric–lifecycle-oriented business model, supported by ICT, in which product data are shared among actors, processes and organizations in the different phases of the product lifecycle for achieving desired performances and sustainability for the product and related services [1, 12]. Generally, product lifecycle consists of three stages: beginning of life (BOL), middle of life (MOL), and end of life (EOL) [12]. BOL includes design and manufacturing; MOL includes product usage, service and maintenance; and EOL includes the timespan when products are disassembled, remanufactured, recycled, reused, or disposed [13]. Traditionally, PLM systems are developed based on a centralized framework provided by third party, such as Windchill, Teamcenter etc. It helps practitioners choose and implement PLM applications that best suit their company's needs, such as document management and product relational data management [14]. Based on the time line, the history of the PLM development can be summarized as: product data management (PDM), web-based PLM, multi-agent-based PLM, and cloud-based PLM. There are a lot of studies focusing different stages of the PLM developments. Some remarkable studies are listed as follows.

The prototype of PDM originated in the mid-1980s and was generated from the fields of CAD/CAM and engineering design [15]. Originally, it was designed to solve the storage and retrieval problems of a large number of product drawings produced by CAD, as well as version constraint issues for such files. For instance, to structure data in reusable and unified forms inside native three-dimensional CAD models, Alemanni et al. developed a method for supporting the Model-based definition implementation using quality function deployment approach [16]. It aims at suppressing of redundant documents and drawings, better data consistency, better product/process virtualization, and better support for all computer-aided technologies tasks under engineering and manufacturing disciplines. After initial development, the design schemes need to be verified by the CAE and expert experience, etc. Therefore, Maropoulos and Ceglarek reviews the standard definitions of verification and validation in the context of engineering design and progresses to provide a coherent analysis and classification of these activities from preliminary design, to design in the digital domain and the physical verification and validation of products and processes [17]. It demonstrates how complex products are validated in the context of their lifecycle. With the development of Internet, web-based PLM started to rise. For example, Vezzetti proposed a structured analysis of Web-based solutions to promote a unique 3 D digital standard model capable of sharing product and manufacturing data more effectively [18]. It provided a qualitative evaluation of the different Web based visualization solutions existing in the PLM context based on the four dimensions, including visualization, security, user interaction, customization and performance. In the stage of multi-agent-based PLM, Monticolo et al. illustrated a collaborative workstation design approach integrating knowledge based on engineering process using a Multi-Agent System to develop a knowledge engineering system integrated into a PLM environment [19]. The Multi-Agent System allows capitalization, and to annotate knowledge according to the actions of the designers inside a PLM environment. It can be applied to improve ergonomics and collaborative design in industrial areas. More recently, enabled by the concept of cloud computing, Holtewert et al. developed a federative, secure and cloud-based platform for distributed service-oriented applications (PLM) in plant operation [20]. It presented the platform by the description of the transformation process to the networked factory. They evaluated their platform based on the standards such as consistency, integrated security across all components, community cloud for IT-decentralization respectively data, cooperation and competence distribution.

On the other hand, in the PLM industrial application, Gomez et al. applied to model the Hartford SMC5 machining center using the software Siemens NX 9 . A validation procedure of the model is provided by modeling, simulating, and executing the manufacturing process of a selected workpiece with complex surfaces [21]. Sakao et al. aims at proposing an innovative and practical method to support manufacturers in the design of a product/service system (PSS) for resource efficiency and sustainability [22]. The intention is that the method be implemented as an add-on feature for commercial PLM (product lifecycle management) software, with a lifecycle focus, including calculation of lifecycle cost (LCC). In order to develop the PLM commercial software for SMEs, Soto-Acosta et al. presents an example of a successful implementation of a self-developed PLIM Framework in a SME from the manufacturing industry [23]. In order to provide an assembly context knowledge to support life-oriented product development process, Demoly et al. describes a novel framework for an assembly-oriented design (AOD) approach as a new functional product lifecycle management (PLM) strategy, by considering product design and assembly sequence planning phases concurrently [24].

However, the centralized PLM systems can hardly satisfy the tendency of the openness of communication and information along the product lifecycle. Furthermore, there are a lot of disperse product information along the distributed lifecycle. It is hard for the stakeholders to capture all the useful product information in a single third-party PLM system. Moreover, trust is always the foundation of cross-company cooperation along the product lifecycle. The party might have concerns about put valuable information in a third party. Therefore, it is necessary to develop a decentralized platform to cover the disperse stakeholder in the product lifecycles.

2.2. Industrial blockchain

Satoshi Nakamoto proposed the blockchain concept as a fundamental technology a digital currency, i.e., bitcoin [25]. It has the advantage of high security, irreversibility, distributivity, transparency and accuracy [8]. It also realizes the mining and trading of bitcoins by constructing a data structure and encrypting the transmission of transacted information [26]. Data encryption is used to ensure that updating or deleting existing transactions is prohibitively expensive, making the blockchain tamper-proof [27]. The data block is maintained by the nodes with the maintenance function. There are no centralized management agencies, as the rights and obligations of any node are equal. It is suitable for the storage of data that require identification and verification. It enables participants to establish a decentralized consensus with the sequence of events and the status of the transaction [28].

Beyond the finance field, blockchain has shown the potentials for transforming resources and services in many other fields. For example, Bahga and Madisetti present a decentralized, peer-to-peer platform called BPIIoT for Industrial Internet of Things based on the Block chain technology [29]. With the use of Blockchain technology, the BPIIoT platform enables peers in a decentralized, trustless, peer-to-peer network to interact with each other without the need for a trusted intermediary. Sikorski et al. explored the applications of blockchain technology related to the I4.0 and presented an example where blockchain is employed to facilitate machine-to-machine (M2 M) interactions and establish a M2 M electricity market in the context of the chemical industry [30]. It concludes that this technology has significant under researched potential to support and enhance the efficiency gains of the revolution and identifies areas for future research. Bocek et al. presented a start-up, modum.io, that uses IoT sensor devices leveraging blockchain technology to assert data immutability and public accessibility of temperature records, while reducing operational costs in the pharmaceutical supply chain [31]. The sensor devices monitor the temperature of each parcel during the shipment to fully ensure GDP regulations. All data is transferred to the blockchain where a smart contract assesses against the product attributes.

To achieve secure information and service sharing, Li et al. proposed a knowledge and service exchange framework based on the blockchain [32]. The proposed framework incorporates the recent development in edge computing technologies to achieve a flexible and distributed network. With the blockchain technology, it provides standards and protocols for implementing the framework and ensures the security issues. Enabled by those advances, the blockchain-based platform is developed by the researchers to supports in the exchange of knowledge and services [33–34]. Similarly, blockchain enabled services' selection and transaction are presented a scenario that blockchain can be used as a tool in the knowledge and service sharing between the service provider and servicer consumer [35].

As for the supply chain provenance, Francisco and Swanson used the Unified Theory of Acceptance and Use of Technology (UTAUT) and the concept of technology innovation adoption as a foundational framework for supply chain traceability [36]. A conceptual model is developed and the research culminates with supply chain implications of blockchain. Kim and Laskowski make a case for why ontologies can contribute to blockchain design [37]. To support this case, we analyze a traceability ontology and translate some of its representations to smart contracts that execute a provenance trace and enforce traceability constraints on the Ethereum blockchain platform. To maintain inventory of the aircraft's individual segments and monitor the performance, Madhwal and Panfilov demonstrated the necessitation of having decentralized Blockchain system [38]. It will help to achieve a transparent network of aircraft's part's supply and reduce the risk of availability of aircraft segments in black market and help the analysts to analyze the supply, demands, source of availability of aviation parts and method to procure them from the right sources. Mattila et al. offered new insights into product-centric information management and showed that blockchain technology can have useful applications in the architectural design of industrial platforms [39]. A conceptual implementation of a distributed agent-based product-centric information management system has been discussed. Distributed agent-based information architectures make product information accessible in a controlled manner over the Internet. This decentralized platform model with trust opens up new avenues for discussion on the topic of multi-sided platforms, especially for durable and capital goods industry sectors.

In conclusion, blockchain has versatile potentials to apply in many fields. Firstly, its data structure can record the events in a verifiable and permanent way by applying a cryptographic algorithm. Its design is essentially based on the resistance towards the modification of data. Once the transaction is produced, it cannot be changed. Secondly, a blockchain provides a beneficial transaction mechanism based on the smart contract. It facilitates transactions among enterprises alliance in an automatic way [40]. Thirdly, a blockchain creates a new type of P2P communication network between members. This P2P network helps users to conduct their own data/transactions without any third party. Therefore, blockchain technology improves the PLM and thus plays an important role in the collaboration process. In here, comparing to the traditional blockchain technology, we proposed the definition of industrial blockchain as the use of blockchain technology in the industry with the integration of IoT, M2 M, and efficiency decentralized consensus algorithms. We use this industrial blockchain to create a bridge to link the parts in the product lifecycles.

2.3. The principle of on-chain or off-chain

Blockchain provides the stakeholders with an open platform, tamper-proof traceability data, regulatory-compliance checking, etc. However, there are private datum which cannot be stored in blockchain publicly. This leads to an important issue that what should be on-chain or off-chain. Two factors are important to solve this issue, including performance and privacy [41]. On the one hand, performance depends highly on the blockchain's deployment. Notably, there are three types of blockchain network that have been introduced, namely, public, consortium and private [42]. The performance of those three blockchain network are totally different. In public blockchain, the comparatively slow speed for transaction confirmation is far behind the huge metadata generation in industry. For example, Ethereum supports roughly 15 transactions per second, which is rather slow in industry. The consortium blockchain is developed by involving limited nodes management. The performance of transaction confirmation is a big advantage to satisfy the requirement of limited alliance members. The private blockchain network is developed for a specific organization with a high-security system. However, it can hardly conduct cross-company boundaries. Therefore, consortium blockchain due to its features of low cost to maintenance, high transaction speed and scalability is acceptable for industrial application [41]. On the other hand, privacy is another concern when deciding a data on-chain or off-chain. Private data should not directly put on-chain. For example, the sensitive raw data must be personally kept, such as traceability certificates and photos. However, the company has the motivation to show the capacity or qualification to the public. Therefore, we suggested a solution that the raw data is off-chain, whereas its hash of the raw data is on-chain [43]. It can not only guarantee the security of the key data, but also prevent the potential data-tampering through the recorded hash.

Based on the principles above, we make a standard for the information on-chain or off-chain as shown in Table 1. We choose the privacy and amount as the standard for data on-chain or off-chain in the proposed architecture. For example, the co-creation process refers to the highly private data and the amount of design scheme is large. Therefore, it is necessary to protect the company's intellectual properties and make it off-chain; the necessity of data for on-chain is low. Therefore, we put the data of design scheme off-chain, meanwhile the hash of the data needs to be put in the chain. This is because it can guarantee the security of the raw data and provide a smooth sharing environment for the stakeholders. On the other hand, the quality-related data, such as manufacturing quality information, logistics information, recall data of product and certificate, needs to be put on-chain due to the requirement of open regulation and reputation. Smart contract, as an electronic contract made by the stakeholders, should be stored in the blockchain network publicly. This helps to validate and execute the content of the contract with a consortium rule.

Table 1
The information on-chain or off-chain based on the standards.

Data Type	Privacy	Amount	On-chain or off-chain
Design scheme	High	Middle	Off-chain
Manufacturing quality information	Middle	High	On-chain
Logistics traceability (origin, producer, components)	Low	High	On-chain
Recall data	Low	High	On-chain
Smart contract	Null	Middle	On-chain
Certificate	Low	Low	Off-chain

3. Methodology of the proposed architecture

3.1. The architecture of the proposed platform

In order to achieve the open and secured information integration and sharing among the product lifecycles, a conceptual framework based on blockchain for the PLM is proposed in this paper. As shown in Fig. 1, the proposed framework consists of five layers, including perception layer, off-chain layer, blockchain layer, application layer, and service layer.

We present a general product lifecycle at the bottom of Fig. 1. Based on the [12], we divided the lifecycle as three parts: BOL, MOL and EOL. Particularly, BOL includes marketing, design, manufacturing and packaging. MOL includes warehouse & logistics, consuming and maintenance. EOL includes product recycling and reuse. Furthermore, we provide four corresponding services for the four processes based on blockchain, as shown in the service layer, including product co-creation, quick inquiry of tracking and tracing, product maintenance and product recycling.

The perception layer is one of the most important input sources of the proposed platform. It is used to collect the data in the product lifecycle environment, including the manufacturing workshop, warehouse logistics & transportation etc. It consists of various IoT devices and smart assets, e.g. QR code, RFID tags and readers, sensors, GPS etc. The collected data deliver to the smart gateway. Smart gateway is a middleware between the IoT sensors and the cloud server [44]. Traditionally, it has the function of transferring the collected data to the local and/or cloud databases and delivering the feedback to the programmable logic controller (PLCs). Here we refer it as smart gateway to defining the collected data, configuring the tools for data preprocessing, analyzing the pre-set data and executing the feedback. The data and information provided from the perception layer will be transmitted to the off-chain layer for further processing in order to upload to the blockchain network.

In off-chain layer, the collected data will be processed in the blockchain information service. As shown in Fig. 1, this component contains four key functions, including data validation, data cleaning, data broadcasting, and capture & query interface. In a simple scenario, data from the perception layer send to the off-chain layer; after being preprocessed in the BIS, such as validation, cleaning, and encrypting, the final hash data is created with the appropriate keys and for enquiring via blockchain the capture & query interface; finally, the hash data and original object data (refers to the data from perception layer) broadcast to the blockchain network. Once they are approved by the consensus algorithm, the hash data store in the blockchain network. The original object data store in the cloud storage environment in the off-chain.

Blockchain network layer is the core component of this architecture. It contains Smart Contract, Consensus Protocol, Decentralized Application (DAPP), and Cryptography, etc. Firstly, smart contract is a computer protocol intended to digitally facilitate, verify, or enforce the negotiation or performance of a contract. It allows the performance of credible transactions without third parties. The setting of the smart contract needs the consensus process among the parties. Secondly, consensus protocol sets at the very beginning of the system. It is the algorithm to reach the agreement among nodes in the blockchain network. Thirdly, DAPPs are distributed internet applications which runs on decentralized peer-to-peer network and its code base is publicly open for others as an open source to be accessed and customized. It can cryptographically store the data and operation records if the data are private and sensitive. Fourthly, cryptography is a tool widely used in blockchain network with varied functions, such as protecting private data, digital signature etc.

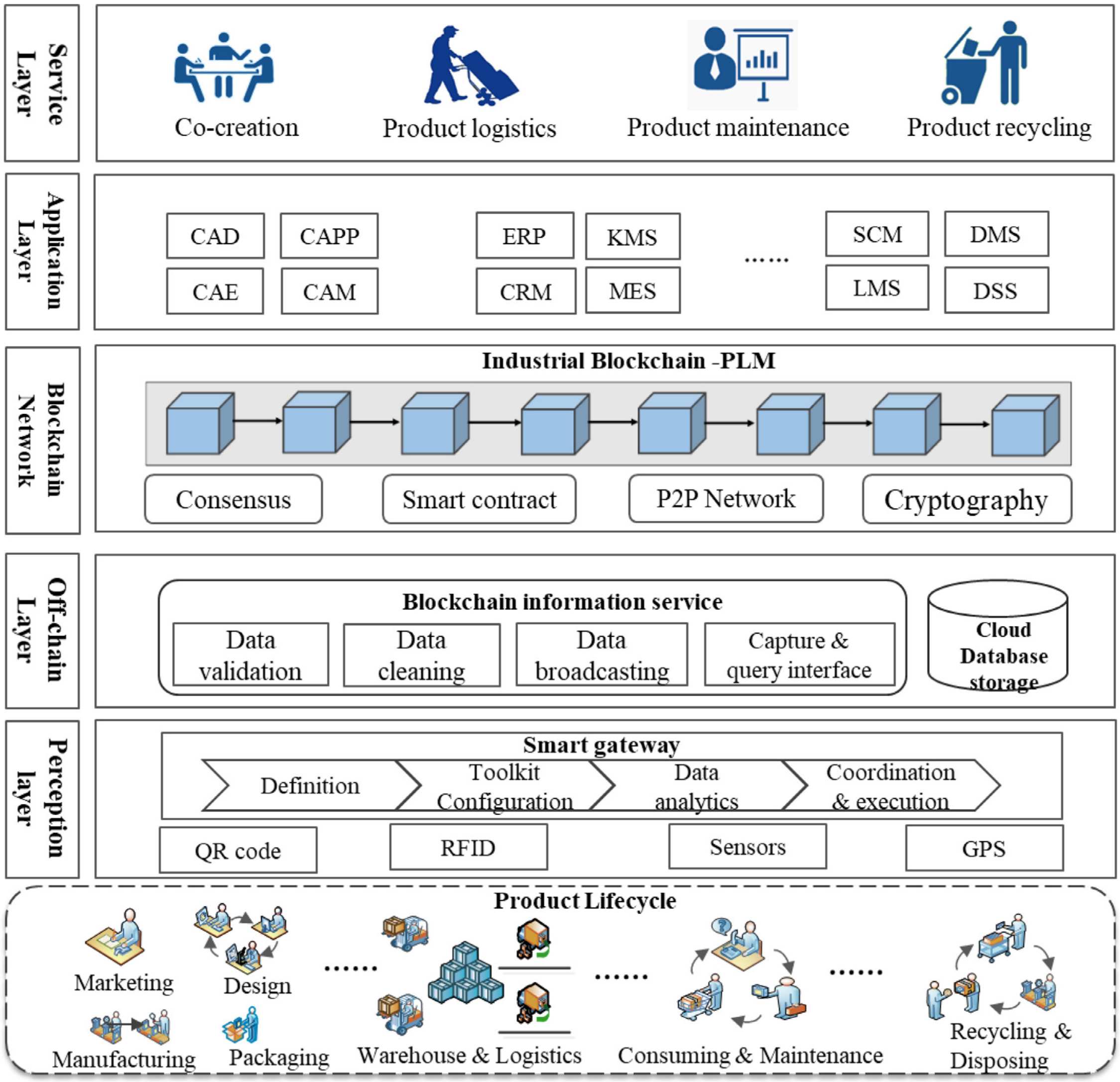

Fig. 1. The architecture of the proposed blockchain-based PLM.

The application layer is composed by a series of services and software products provided by the companies. These services and software products are connected with different stages of PLM according to their different functionality. For example, they include software for Computer-Aided Engineering, Computer-Aided Design, Computer-Aided Manufacturing, Computer-Aided Process Planning (CAE/CAD/CAM/CAPP) and Manufacturing execution system (MES). The data from the software are related to co-design and co-creation of PLM. Some data from Supply Chain Management System (SCM), Logistics Management System (LMS) and Enterprise Resource Planning (ERP) are associated with quick and accurate tracking and tracing (QAT^2) stage. The proactive maintenance and regulated recycling include; Customer Relationship Management System (CRMS), Document or Data Management Systems (DMS) and Decision Support System (DSS). Besides, there are many other proprietary software and systems. The application layer works closely with the blockchain network and off-chain layer. The data in the application layer can be transferred to blockchain network through BIS. Meanwhile, the data in the blockchain and application layer can be designed based on the principle of on-chain or off-chain, as illustrated in literation review.

The service layer consists of four key services, including product co-creation, real-time tracking and tracing, product maintenance, and product recycling. As mentioned before, they are directly related to the three critical stages in the product lifecycles (BOL, MOL, EOL). Based on the timeline of product lifecycle, we choose the four most representative services to facilitate its operation with blockchain technologies. In BOL stage, it includes the marketing, designing, manufacturing and packaging. It is a typical co-creation process. Therefore, we propose a co-creation blockchain to provide a platform for the stakeholders involving the BOL. In MOL stage, it includes the warehouse & logistics of product and product maintenance. We propose the quick tracking and tracing blockchain to provide a whole product logistics information and guarantee the product safety. In product maintenance stage, it relates to the product consuming and maintenance. As the longest stage in the PLM, it involves many parties, including product research team, technical supporter and technical engineer. To provide a proactive product service, we use blockchain to record the feedback data from the end-consumer. The analysis engine and prediction model can then be used for three kinds of product maintenance, including preventive maintenance, corrective maintenance and predictive maintenance. In EOL stage, we propose recycling blockchain to provide a regulated recycling process. Notably, we illustrate the cycle into six steps, namely recycling, verification, processing, designing based on recycling, reproduction and re-sale.

The communication between the different applications with the blockchain data and off-chain data divided into two aspects. Firstly, the communication of different applications with the off-chain data conducted through the internal cloud databases. The off-chain data refers

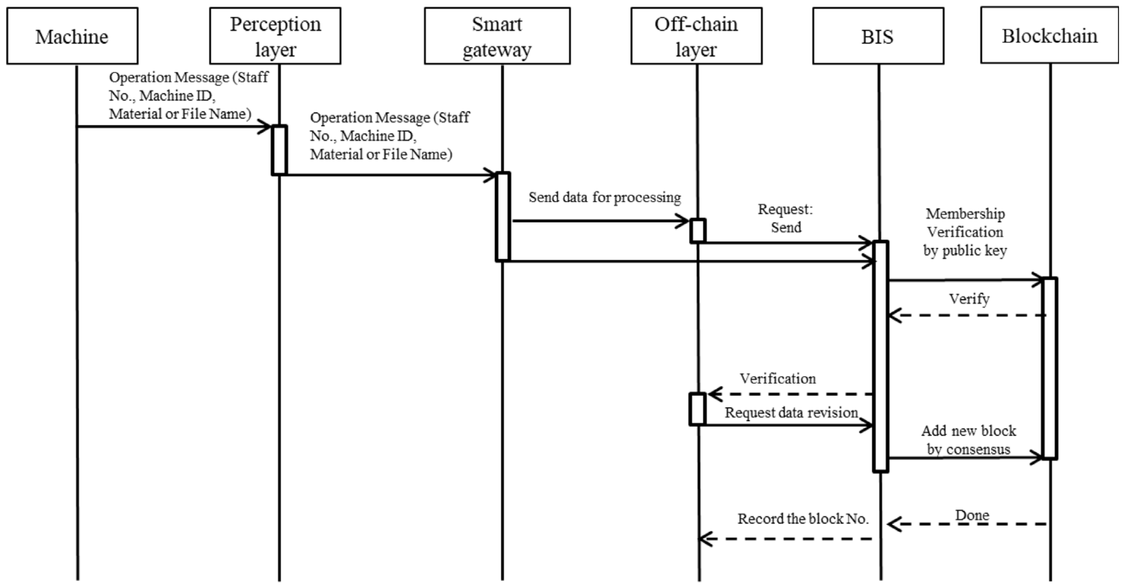

Fig. 2. The information flow from a machine-level to blockchain network.

to the relevant data stored in the local/cloud databases of a specific enterprise. Secondly, the blockchain data consists of two categories, on-chain data and object data. The object data refers to the real data, which is stored in the distributed databases. Due to the limited size of each block, the on-chain data refers to the hash, the storage address of the object data etc. It means that, if the different applications need to access to the blockchain data, it can search through the on-chain data. Thus, it not just keeps the authentication of the object data, but also save the storage size of each block.

3.2. The technical solution of the proposed platform

To clarify the technical process of proposed architecture, we illustrate it through the enterprise-level and product-lifecycle-level, as shown in Fig. 2 and Fig. 3, respectively.

In the enterprise-level, the connection of all parts is illustrated via sequence diagram of UML shown in Fig. 2. Firstly, the data of product, process and resources send to smart gateway by IoT sensors and RFID etc. here we use the machine to represent all the data sources. Smart gateway is a physical device which serves as the connection point between the cloud and sensors. The connectivity protocols between those sensors and smart gateway are usually wireless based method, such as WIFI, Bluetooth, Zigbee etc. Meanwhile, smart gateway can play a role in storing and preprocessing the raw data. Secondly, the preprocessed data transfers to the off-chain layer. Usually, the messaging protocols between gateway and cloud are Plain HTTP, MQTT etc. Thirdly, the data in the cloud can be further processed and stored. The owners of the cloud decide which data will be sent to BIS. Fourthly, BIS put the data into a block according to certain structure, and generate legal block header information. Then the generated blocks upload to blockchain network based on predefined smart contract. Finally, the new blocks generate by the membership verification and public key. Specifically, the data which will be put in blockchain network need be verified by the consensus algorithms. Once it is not qualified, the feedback will be sent to BIS and off-chain layer.

In the product-lifecycle-level, the information flow has been divided into three stages, namely BOL, MOL, and EOL, as shown in Fig. 3. Each stage contains various product-related activities, including the product design, product manufacturing, and warehousing management etc. Also, each product-related activity contains a lot of product information. Take product design as an example, it contains design instructions, 2 D design drawings and models etc. They are usually stored in CAD-related databases. In a simple scenario, we use the product collaborative design to clarify the mechanism of how to integrate blockchain-based PLM with existing applications.

- ***Design data on-chain***: we consider that a block is created each time when a product designer finishes or updates the design tasks. In the blockchain, a block consists of block header and block body. In the proposed industrial blockchain-based PLM platform, block header can carry the information, such a hash of previous block, a time stamp and versions etc. Block body can carry the limited-size

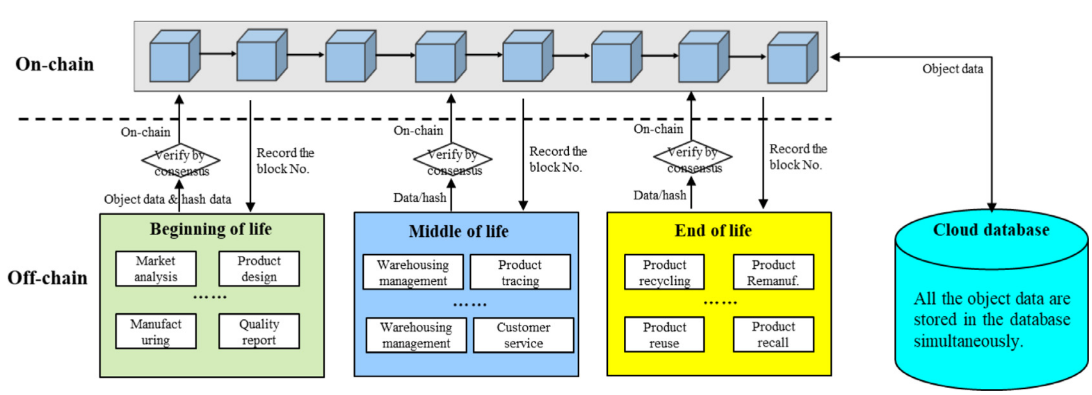

Fig. 3. Three stages of product lifecycles.

information, such as the product name, designer name, limited product data and its linkage to other data source. Simultaneously, the finished/updated product design files, such as the geometric model, design requirements etc., will be stored in the CAD-related cloud databases.

- ***Access the design data***: if the other collaborative designers need to access the relevant design files, they can firstly search through the industrial blockchain-based PLM platform. Then they can use the data linkages to access more large size design files in the cloud databases through the predefined application programming interface (API). Notably, the collaborators cannot make changes to the design files neither in blockchain nor in cloud database. This is because they are linked together through the hash value. Any change will lead to an incompatibility to the proposed platform.

By this, it can create a collaborative decision-making environment in blockchain-based PLM and provide opportunities for the stakeholders to timely and accurately work on the collaborative design tasks. It also fosters a permeable traceability of a specific product design documentations across multi-entities.

4. The proposed key services

This section discusses the four typical services in the product lifecycle, including blockchain-enabled co-creation service, blockchain-enabled quick inquiry of tracking and tracing service, blockchain-enabled maintenance service and blockchain-enabled recycling service, as shown in Fig. 1. They are the most representative activities in the three stages of BOL, MOL and EOL [23].

4.1. Blockchain-enabled co-creation service

Co-creation is a concept proposed by Prahalad and Ramaswamy in Harvard Business Review [45]. Within their study, they defined co-creation as “The joint creation of value by the company and the consumer; allowing the consumer to co-construct the service experience to suit their context” [46]. However, there are different challenges in the emerging I4.0. One of the biggest challenges is how to meet the open but secured co-creation environment. Hence, we propose a new blockchain-based co-creation service. It aims to provide an open but secured environment for allowing the multiple stakeholders to meet the massive individual requirements.

To contrast, there are two steps to achieve the joint creation of value in traditional co-creation: contribution and selection. Contribution means that a company needs to convince its customers to contribute with their ideas. However, receiving contribution is actually quite hard because of less willingness and motivation to the customers. To solve this problem, we use blockchain-based platform, which provide a co-operation mechanism for customers and company. The customers can achieve their customized demands with co-creation in this platform. Therefore, they are more willing to contribute with their ideas. Because the transparent and secured platform can guarantee the benefits of the participants. Both the vendors and consumers can involve in this joint creation to satisfy their demands. To achieve the blockchain-enabled co-creation service, we illustrate the process as shown in Fig. 4:

- The ideas proposed by the consumers need to be submitted to the platform with a unique digital signature.
- Predefined smart contract can initially verify the ideas and put it at the local blockchain.
- The third step is that the new generated blocks will be broadcast to the blockchain nodes for reach consensus.
- Once the block reaches an agreement by the pre-set consensus algorithm, the block is generated in the blockchain network.
- Then the on-chain information could be predefined based on the requirements from the companies.
- Finally, the company can make the selection based on the information in the blockchain. Once the ideas are adopted, the author can get the rewards. And this transaction will also be recorded in the blockchain network as to attract more involvers.

To clarify the mechanism of blockchain-enabled co-creation service, we present a typical co-creation scenario: “There are a blend of ideas from direct consumers or viewers who in turn creates new ideas to optimize product. The designers from different companies need to cooperate together to satisfy the demands from the consumers. Simultaneously, the designer must cooperate with the manufacturers to produce a qualified product.” Therefore, there are three kinds of cooperative forms in this scenario. The first one is the cooperation between consumer and designer, shown in Fig. 4. It has to involve the CRM, CAD and CAE, which is a process turning the consumers’ preference into the 3 D drawings. The second is the cooperation among the designers across company, involving the CAD files sharing and matching. The final one is the cooperation between designer and manufacturer. It involves many applications, such as CAD & CAE in design phase, MES & QMS in the manufacturing phase, etc., which is a process turning the 3 D drawings into real products. During these processes of cooperation, there are a lot of sensitive data which the company are reluctant to open due to risk of leakage to unauthorized party. That is why the third-party-based PLM solution can hardly satisfy the security requirements. In this paper, blockchain is used to guarantee the security. As illustrated in Table 1, the original sensitive data can be sent to the authorized party via blockchain-based communication protocols. The sensitive data along with the relevant transaction information can be encrypted into hash (256 irregular characters and numbers), which will be put on-chain. Therefore, proposed platform provides an open but secured environment to facilitate the cooperation.

4.2. Blockchain-enabled QAT^2 service

To monitor products information timely, we proposed the QAT^2 service, as shown in Fig. 5. The importance of tracking and tracing of products is considered quite high for manufacturing firms in terms of customer service and essential for managing logistics networks efficiently [47]. There is now growing interest in blockchain ‘distributed ledger’ technology. It helps businesses to encode a products’ movement and environmental condition history in a secure, immutable record.

To track and trace a specific product, an inquirer conducts an inquiry in the search engine by inputting relevant product information, such as the batch number, product name etc. The information in the blockchain network will be retrieved in order to find the relevant product information, such as the origin of raw material, manufacturing quality report and logistics information etc. Those data are collected from the product lifecycles by the IoT technologies. Moreover, the BIS plays the role as a middleware to transfer those data to the blockchain network, as illustrated in the former section. Finally, the searched results from the blockchain-based distributed database include product name, producer, place, time and quality information. They are the data pre-updated by the stakeholders in the product lifecycle. The results will be used as the input of the smart contract. Once the analysis model detects the emergency events, the output will give directly to the consumers and feedback to the producers simultaneously.

4.3. Blockchain-enabled proactive maintenance service

Product maintenance is the longest stage in the PLM. It involves many parties, including product research team, technical supporter and technical engineer etc. To achieve the blockchain-enabled proactive maintenance service, we illustrated the mechanism as shown in Fig. 6.

To achieve the product proactive maintenance, IoT technologies, such as the sensors, RFID, are used to monitor and collect the data from machine and product embedded information devices (PEID). The IoT

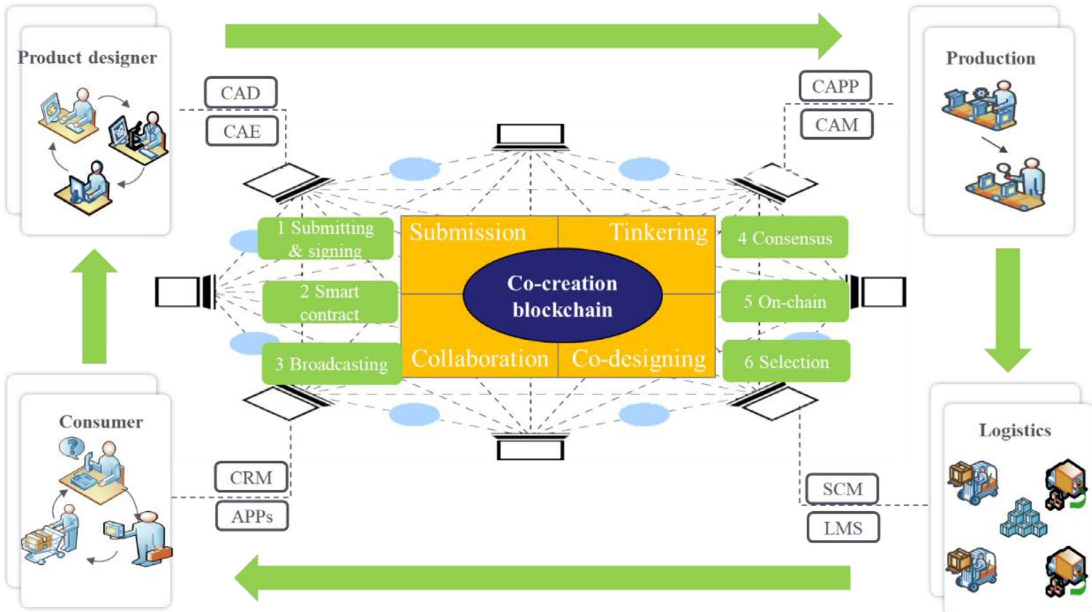

Fig. 4. The collaborative development based on co-creation blockchain.

edge is connected with the BIS. As illustrated in Section 2, the flow of data in BIS has three directions, including enterprise cloud database (DB), enterprise information systems (EIS) and blockchain network. The cryptography, as an important component in blockchain, is used here to provide identification verification by digital signature. Moreover, the consensus is used to generate the on-chain blocks and guarantee the consistency of the global blockchain records [48]. The smart contract is used for analyzing the data collected in the product utilization to provide a better product service. In a simple scenario, we show the creation of smart contract to achieve the proactive maintenance at the top of Fig. 6. The maintenance agencies, such as the producers or a third-party maintainer, firstly need to reach an agreement about the standards and requirements for a specific product's maintenance. After that, they could create the smart contract to the blockchain network. Once the new generated data in blockchain, which is collected by IoT technologies, invokes the conditions in former contract. The smart contract can operate automatically, such as machinery monitoring and diagnosis, maintenance alert, and maintenance service calling etc. Thus, the maintainers can conduct their work ahead of the machine breaks down. Moreover, every state of the machine and each maintenance record will be stored in the blockchain. It not only helps the maintainers to know the history of the machine/product, but also facilitates the managers to make decisions, such as updating or replacing etc., based on the real-time machine condition.

4.4. Blockchain-enabled regulated recycling service

Recycling is the process of converting waste materials into new materials and objects. Recycling can prevent the waste of potentially useful materials and reduce the consumption of fresh raw materials. Therefore, it is not only a potentially cost-saving method for the company, but also are of great benefits to the environment. As an important role in PLM, its aim is to close the loop and recycle materials back into the manufacturing process.

Traditionally, the recycling is often conducted by third-parties [49]. However, third-party systems often lack transparent recycling mechanism. For example, the initial bid is provided by the system without any visible standards. The product owner might have the concerns with the blind offer. Furthermore, there is often scarce of effective regulation mechanism for processing the recycling product. As a result, the product is wasted or thrown away by the owner, which could lead to a resource wasting and potential environment threats.

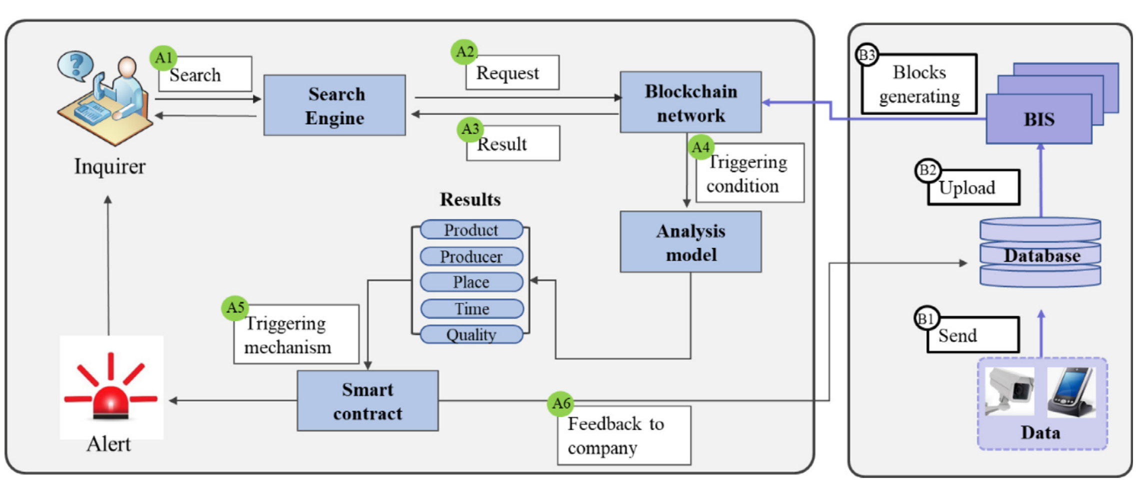

Fig. 5. Blockchain-enabled real-time tracking and tracing service.

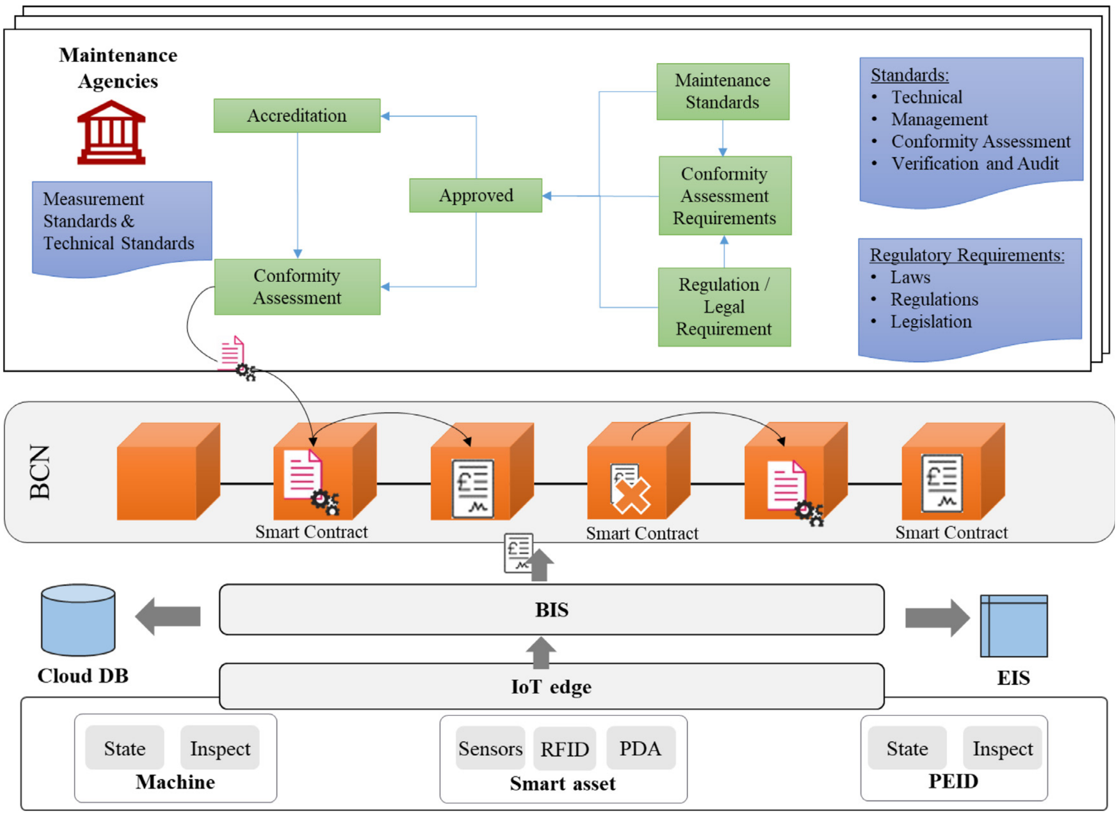

Fig. 6. Blockchain-enabled proactive maintenance service.

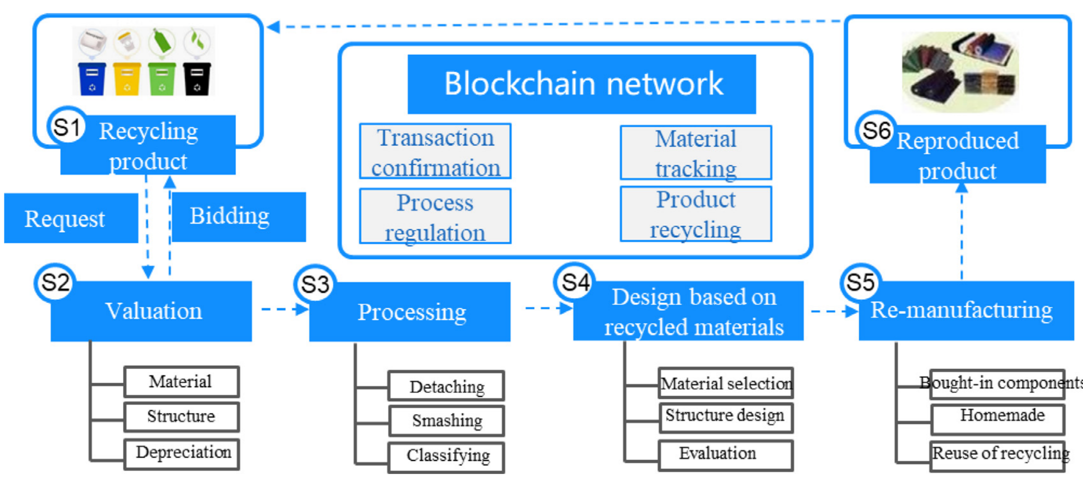

Fig. 7. The mechanism of recycling for design based on blockchain.

To address these challenges, we proposed the blockchain-enabled regulated recycling service as shown in Fig. 7. To build the closed loop in the product recycling, we divide it into six parts, including recycling product, verification, process, design based on the recycling, reproduction and reproduced product. Firstly, we build the clear standards for the product recycling to motivate the willingness of the product users. For example, the standards show a clear price ranges by the different criteria, such as the using time, brand, material etc. Secondly, every transaction of the product recycling will be recorded in the blockchain network. Thus, it provides the product owner with the transparent and trustable recycling mechanism. Once the product owners know more about how the product is disposed of and the beneficial recycling mechanism, they prefer to add the product into blockchain-enabled regulated recycling service rather than throw it away directly.

After the recycling, the process of the product is another key to achieve the closed loop. Due to features of the complexity in materials and variety in structures, it is difficult to process these products to reduce even prevent the environment pollution. Therefore, the effective regulation is necessary for the recycling product processing in order to achieve the environmental-friendly reuse. In this paper, blockchain is used to provide a transparent and trackable records for the process and reproduction. For example, blockchain can be used to record the classification of the recycling product and the methods of processing, such as smashing, detaching etc. As for the design based on the recycling and reproduction, they can be operated based on the same logic with the co-creation service as mentioned above.

5. Simulation and evaluation

5.1. Experiment description

To evaluate platforms based on data exchange and platform openness, we used Hyperledger Fabric Java SDK for developing the pilot implementation of our platform. In the pilot implementation, we mostly focused on the blockchain network to show the effectiveness and efficiency of applying blockchain technology into PLM platform. The chosen JDK version is "Java 1.8.0_121″ and the integrated Development Environment is mainly Eclipse. As an open source blockchain technology, it provides a number of SDKs to support a variety of programming languages. To utilize the open source Hyperledger Fabric Java SDK as a development platform for blockchain services, we configure the fabric environment, by downloading the Fabric-SDK-java toolkit, and use IntelliJ IDEA as the development IDE. We use the go language for smart contracts, and Go ChainCode toolkit to write related smart contracts. As for the BIS, its role acts like a smart hub in the network integration. Notably, we envisage that BIS is enabled to deliver the all data from IoT devices/edges to the blockchain network in a trusted and secured method under current pilot implementation. More detailed development tools are presented in Table 2.

In this experiment, five master nodes and 100 users were defined as end users on the developed blockchain network. Data of different sizes are considered to be 4, 8, 16, 32 and 64 bits with 1000 transactions. Chaincode on the Go (a programming language) is used to develop smart contracts. The simple structure of this code is shown in Fig. 8. It has two functions, Init and Invoke. "Init" is called when the chain code is first installed or when the existing chain code is upgraded. "Call" means the condition for starting this smart contract. When the predefined conditions are met, the smart contract will automatically send data to the data user, that is, once the analysis model detects an emergency, the output will be directly sent to the consumer and feedback to the producer at the same time.

Consensus in Hyperledger Fabric is broken out into 3 phases: Endorsement, Ordering, and Validation. Hyperledger Fabric supports pluggable consensus service for all 3 phases. Applications may plugin different endorsement, ordering, and validation models depending on their requirements. In particular, the ordering service API allows plugging in pBFT-based agreement algorithms [43]. The ordering service API consists of two basic operations: broadcast and deliver. In addition, Member Service Providers (MSP) was used in order to improve security and provided openness platform for users. It is defined as a component that aims to offer an abstraction of a membership operation architecture. In particular, MSP abstracts away all cryptographic mechanisms and protocols behind issuing and validating certificates, and user authentication. An MSP define their own notion of identity, and the rules by which those identities are governed (identity validation) and authenticated. Therefore, Redundant Byzantine Fault Tolerance consensus mechanism was used on the proposed platform.

5.2. Experimental evaluation and comparison

We evaluated our proposed platform in terms of qualitative and quantitative ways. The proposed platform is compared qualitatively with five main existing platform, including traditional PLM, web-based PLM, agent-based PLM, cloud-based PLM, Blockchain public cloud PLM and the proposed PLM. According to the existing definitions for PLMs' characteristics presented in the literatures, some common key characteristics in PLM, such as scalability, that is, the ease to use or customize and learnability, privacy, ubiquitous access, are selected and compares the proposed PLM with the other existed PLMs. Besides, some criteria which can reflect the cost are also illustrated such as transaction speed. The result of this comparison is shown in Table 3.

Table 2
Development tool for blockchain-based PLM framework.

Software development kit	Fabric-sdk-java, Chaincode
IDE	IntelliJ IDEA, Sublime Text
Blockchain network	Hyperledger Fabric
Cloud server	AWS
other	Fabric-sample, Docker

To highlighted advantages of proposed platform, the proposed platform is also quantitatively compared with the Ethereum public platform by considering two main indictors, namely latency and throughput. They are two key performance indictors (KPIs) to evaluate the performance of blockchain network in the platform [50].

On the one hand, the latency of the proposed platform and Ethereum platform is compared under five kinds of block sizes and transaction arrival rates. Specifically, it includes 4 bits, 8 bits, 16 bits, 32 bits, and 64 bits in block sizes. It also includes 20 tps, 40 tps, 60 tps, 80 tps, 100 tps in transaction arrival rates. Notably, "tps" refers to transactions completed in one second in the proposed platform. Three interesting results can be noticed based on Fig. 9 and Table 4. Firstly, the proposed platform has less latency compared with Ethereum platform under the same transaction arrival rate and block size. As shown in Fig. 9, under the condition of transaction arrival rate "20 tps" and block size "4 bits", the latency of the proposed platform is 640 ms, which is notably lower than the 870 ms of Ethereum platform. More generally, as shown in Table 4, the mean value of latency of proposed platform is much less than Ethereum platform. The reasons can be explained as follows: the proposed PLM platform is developed based on consortium blockchain. The rate of data duplication on the public blockchain is much higher than consortium blockchain; Moreover, the consensus algorithm in the proposed platform has better mining process. Secondly, as shown in Fig. 9, with an increase in transaction arrival rate, the latencies of both platforms were also in an increasing trend, but the increasing rate of Ethereum platform (ET) is much higher than our platform. This is another evidence to prove the better performance of the proposed platform. Thirdly, in both platforms, latency is increased with the increasing block size, but the latency increased significantly until block size is more than 32 bits. It means that the block size has an important but nonlinear impact to the latency. Once its size is over a certain quantity (32 bits), it would increase the latency of the platform dramatically.

On the other hand, the evaluation of throughput is conducted between the proposed platform and Ethereum platform considering different peer quantities. Fig. 10 show the throughput of each implementation for the invoke function when the number of transactions in the dataset is 1000. The proposed platform using consortium Hyperledger platform has a better throughput from 1 peer to 20 peers. The throughput of proposed platform ranges from 165 tps to nearly 250 tps. To contract, the throughput of Ethereum platform ranges from 140 tps to 150 tps. However, we also need to notice that the stability of the proposed platform is not good as the Ethereum. That means the user can experience the fluctuated throughput speed when using the proposed pBFT-based platform.

5.3. Discussion

Conventional PLM systems are implemented based on standalone and centralized systems provided by software vendors. The information of PLM is hardly to be integrated and shared among the cooperating parties. To meet the requirements of the openness, interconnectedness and decentralization of the Industry 4.0 era, this paper proposed an industrial blockchain-based PLM. It created a new type of P2P communication network based on blockchain technology. It can help users to conduct their own data sharing/service exchange in an open environment. Through the experimental simulation, several benefits could be gained by using the proposed platform.

```
function addNewOrderData(uint operateID,        string operatorName, uint machineID,
string materials, uint temperature, uint humidity)
public payable returns(uint stateNum, string message)
        {
                OrderData storage _tempOrderData;
                uint stateNum;
                string message;
_tempOrderData.operateID = operateID;
                _tempOrderData.operatorName = operatorName;
                _tempOrderData.machineID = machineID;
                _tempOrderData.materials = materials;
                _tempOrderData.temperature = temperature;
                _tempOrderData.humidity = humidity;

                OrderDataCollection[operateID] = _tempOrderData; //saving the data

                if((T_LOWER_LIMIT < temperature) && (temperature < T_UPPER_LIMIT)
&& (H_LOWER_LIMIT < humidity) && (humidity < H_UPPER_LIMIT)){
                        // set the message to show that the data save success
                        stateNum = 0;
                        message = "the new data adds successfully";
                }
                else{
                // set the message to show that data save success but some data abnormal
                stateNum = 1;
                message = "There is an data warning occur";
                // when an error of environment occur, sending the error report with the error data and message
                if(temperature < T_LOWER_LIMIT)
                {
                        emit DataErrorWarning(msg.sender, operateID, TLErrorNumber, "the temperature too low");
                }
                if(temperature > T_UPPER_LIMIT)
                {
                        emit DataErrorWarning(msg.sender, operateID, TUErrorNumber, "the temperature too high");
                }
```

Fig. 8. The code sample of smart contract for risk analytics.

Table 3
The typical comparisons with the existed PLM platform in a qualitative method.

Type of PLM/Characteristics	Traditional PLM/PDM [1,14]	Web based PLM [17]	Agent based PLM [18]	Cloud based PLM [19,20]	Blockchain public cloud PLM [32, 43]	Proposed platform
Scalability	✓	✓	✓	✓	✓	✓
Privacy	✓	✓	✓	✓		✓
Ubiquitous access				✓	✓	✓
Credibility					✓	✓
Openness		✓			✓	✓
Interconnectedness & Interoperability					✓	✓
Decentralization			✓			✓
Flexibility			✓	✓	✓	✓
Security						✓
Near Real-Time Big-Data Processing				✓		✓
Software as a Service				✓	✓	✓
Pay-per-use				✓	✓	✓

Firstly, pBFT-based agreement algorithm has a good performance in the consensus process compared with Traditional Ethereum platform. The experimental results show that the latency of the proposed platform is much less than the Ethereum platform under five kinds of block sizes, including 4 bits, 8 bits, 16 bits, 32 bits and 64 bits; the throughput of the proposed platform is higher than the Ethereum platform during the peers (nodes) from one to twenty. Therefore, the proposed platform performs better than the Ethereum one in term of latency of block generation and throughput.

Secondly, we compared the proposed PLM platform with existed PLM platforms in qualitive ways as shown in Table 2. Based on the literatures, we make a comparison in the aspects of scalability, privacy, ubiquitous access, credibility, openness, interconnectedness & interoperability, decentralization etc. We found that blockchain-based PLM platform provided significantly more benefits over many other PLM platforms. It has the advantages to better meet the future requirements of PLM by involving more parties to contribute their parts.

Finally, the four key services have been optimized based on the industrial blockchain technologies, including the co-creation service, QAT^2 service, proactive maintenance service and regulated recycling service. In co-creation service, can blockchain not only provide an integrative platform which allow the producer, transporter and their enterprise information systems to integrate the product information, but also provide an open but secured environment for consumer to jointly create the value to suit their own use. Every contribution by the consumer is recorded in tamper-proof way, which guarantee the benefits for the contributors. In QAT^2 service, the industrial blockchain-based proposed platform provides the traceability service by recording the products' movement and its environmental condition history in a chain-based method, which is secured and immutable. The history of

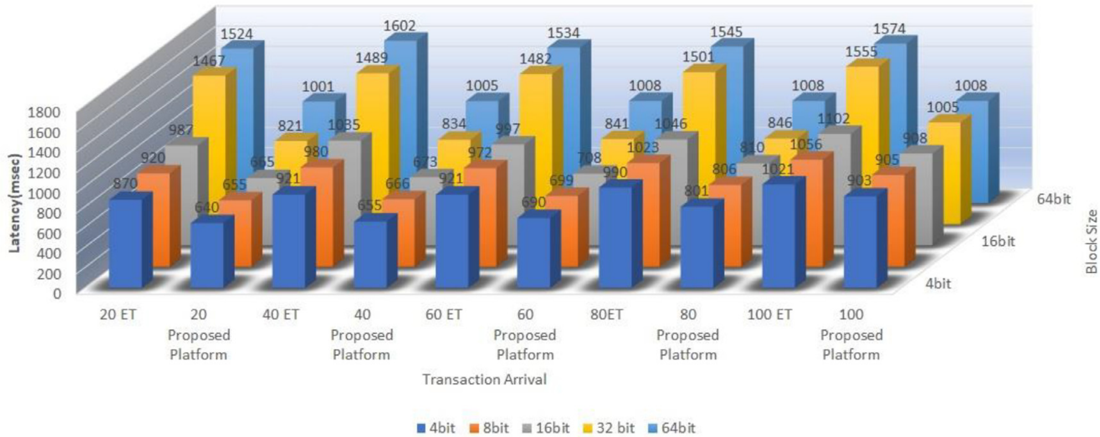

Fig. 9. The latency of various block sizes under different transaction arrival rates.

Table 4
Detail information about latency performance.

		Mean	Standard deviation	Standard error	95% confidence interval
20 (tps) Block size 4 bit	ET	1153.6	315.5	141.09	391.6
	Proposed Platform	756.4	155.07	69.3	192.5
40 (tps) Block size 8 bit	ET	1205.4	315.4	140.14	390.82
	Proposed Platform	766.6	152.2	68.08	189
60 (tps) Block size 16 bit	ET	1181.2	300.1	134.22	372.6
	Proposed Platform	789.2	137.04	61.2	170.1
80 (tps) Block size 32 bit	ET	1221	276.8	123.8	343.6
	Proposed Platform	854.2	87.7	39.2	108.9
100 (tps) Block size 64 bit	ET	1261.6	278.07	124.3	345.2
	Proposed Platform	945.8	55.44	24.7	68.8

the product will be presented as chain-based information from its origin to end consumption. In proactive maintenance service, smart contract is used for analyzing the data from PEID based on the predefined conditions. It provides an automatic fault diagnosis to support the timely proactive maintenance for the product in use. In the regulated recycling, blockchain can make a difference on many aspects during the recycling, such as transaction confirmation, waste material tracking, process regulation in re-production etc. It not only provides a regulated closed loop PLM, but also facilitates the environmental-friendly material reuse.

However, there exist some limitations in our proposed platform. Firstly, we did not fully implement our proposed platform in the real-life use case study, so existing results supported possibility to implement this platform but cannot make quantitative comparison with traditional PLM platforms. Secondly, pBFT-based consensus algorithm is suffering from redundancy issue. Once the nodes increase, the latency of the pBFT-based consensus will increase as well, which hampers the performance of the proposed blockchain-based PLM solution. Thirdly, stability of this proposed platform is not as good as the Ethereum. As shown in Fig. 10, under the same experiment environment, the throughput of proposed pBFT-based consensus has a higher performance than the Ethereum, however, the stability is not good as the Ethereum. That means the user can experience the fluctuated throughput speed when using the proposed pBFT-based platform.

6. Conclusion

In the era of I4.0, an open but secured, interconnective and

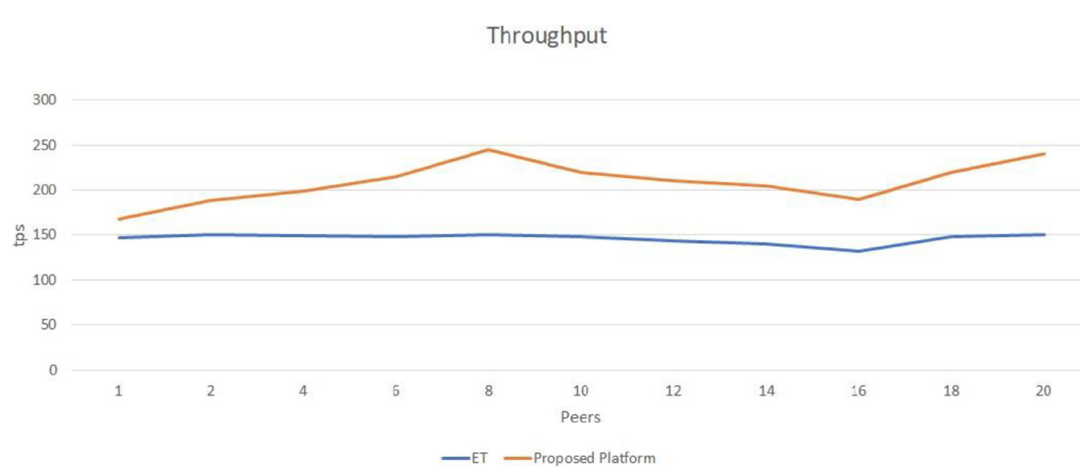

Fig. 10. The comparison of throughout between ET and the proposed platform.

decentralized PLM platform is of great importance to ensure a co-operative environment to managing the entire product lifecycle. Based on industrial blockchain technologies, this paper provides an industrial blockchain-based PLM platform to conduct information sharing and service exchange. The contributions of this paper can be summarized as follows. Firstly, the technical architecture of the proposed industrial blockchain-based PLM platform is developed for achieving the openness, interconnectedness and decentralization. It can not only manage and integrate the information inside the enterprise, but also realize the information and service sharing cross-enterprise. Secondly, customized BIS is used for multi-source and heterogeneous data automatically processing and broadcasting. It can process the various data along the product lifecycle to make a standardized block data. Thirdly, smart contract-enabled transaction executions and alert services facilitate product flows in the product lifecycles. It helps the enterprise to provide instant decision making and support, so as to increase the quality of their products and services. Finally, blockchain-based four key services are utilized to illustrate a closed loop of product lifecycle management, including co-design and co-creation service, QAT^2 service, proactive maintenance and regulated recycling service. The experimental simulation proves that the proposed PLM platform outperforms the existed PLM platforms in term of qualitative and quantitative evaluations. The latency and throughout is much better than the Ethereum.

In the future, the work can be extended from the following two perspectives: technological and organizational. In a technological perspective, the scalability and compatibility of the proposed platform should be further verified and evaluated in a real business environment with more nodes. In this paper, we only consider 5 master nodes and 100 users. However, the more node quantities exist in real business environment. It might affect the performance of the proposed platform, including throughput and latency. Therefore, it is important to consider the scalability and compatibility of the proposed platform when involving more nodes. Secondly, the customized BIS tools should be further explored to support the process and transfer of the multi-source and heterogeneous data. In the pilot implementation, we assume that BIS enables the data transfer in an ideal state. However, the real scenario has more threats to consider, such as the security, messaging protocol etc. And thirdly, the application of smart contract-enabled emergency alert mechanism should also be evaluated more, such as how to update the versioned smart contract, how to quickly response and operation during the occurrence of emergent product incidents. In an organizational perspective, more value metrics need to be considered to measure actual benefits and risks from the final deployed PLM solution, such as the investment risks, return on investment, and user experiences etc. For instance, under the industrial blockchain environment, the potential risks and opportunities in the activities of PLM need more practical analysis.

Declaration of Competing Interest

The authors declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere. There are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address (piersli@foxmail.com) which is accessible by the Corresponding Author and which has been configured to accept emails from the editorial office.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rcim.2019.101897.

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